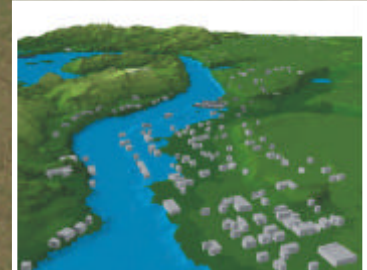
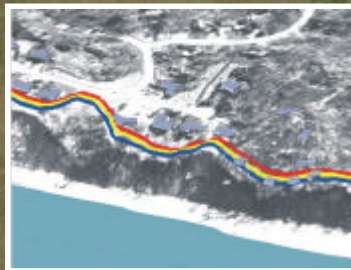


U.S. Army Corps of Engineers  
Detroit District

**Final Report - Fiscal Year 2000**

# **FEPS Development and Application to the LMPDS Prototype Counties**



**November, 2001**

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## 1.0 INTRODUCTION

The Lake Michigan Potential Damages Study was initiated in 1996 by the Detroit District U.S. Army Corps of Engineers (USACE). Figure 1.1 outlines the limits of the study. The goals of the study are to satisfy several key recommendations of the 1986-1993 International Joint Commission Great Lakes Levels Reference Study (IJC, 1993). The primary objective is the evaluation of potential economic damages due to future extreme water levels on Lake Michigan over the next 50 years.



**Figure 1.1 Lake Michigan**

This report has been prepared to summarize Baird's activities related to the Lake Michigan Potential Damages Study in Fiscal Years 2000. The focus of this report is the development of the Flood and Erosion Prediction System (FEPS) and the application of the system to the five prototype counties on Lake Michigan, including: Ottawa, Allegan, Ozaukee, Sheboygan and Manitowoc. The predictive capabilities of the system were utilized to estimate future shoreline position at 20, 35, and 50-year intervals for the three LMPDS lake level scenarios.

Section 2.0 will describe the development of the Flood and Erosion Prediction System, including a description of the various modules and their interactions with the coastal data in the system. Section 3 will discuss the primary datasets utilized in the coastal modeling and the Lake

Michigan shoreline classification. Erosion processes for the cohesive and sandy shorelines on the Great Lakes, and the modeling approach in the FEPS is summarized in Section 4.0.

The results of FEPS erosion modeling for the five prototype counties is discussed in Section 5.0. Section 6.0 presents the methodology and results of the GIS mapping for future shoreline position. The report concludes with recommendations for further data acquisition, development and refinement of the FEPS modules, and future modeling in the Prototype Counties.

## 2.0 THE FLOOD AND EROSION PREDICTION SYSTEM

Section 2.0 of the report discusses the development of the Flood and Erosion Prediction System and introduces the functionality of the various modules in the system.

### 2.1 Development of the Flood and Erosion Prediction System

Given the diverse range of geo-spatial data analysis and numerical modeling tasks required to predict future flooding and erosion hazards, it was not possible to adopt an existing software program for the Lake Michigan Potential Damages Study.

Consequently, a custom application, referred to as the Flood and Erosion Prediction System, was developed by Baird & Associates.

The FEPS is a GIS based deterministic modeling system capable of predicting flooding and erosion hazards for lakes and ocean coasts. In order to facilitate future upgrades to the FEPS and capitalize on existing numerical models, the tools have been developed as a loosely coupled system. The various modules and coastal database are linked together by the FEPS user interface (UI), as described by the schematic diagram in Figure 2.1. The user interacts with the system through the FEPS interface, and the modules listed at the

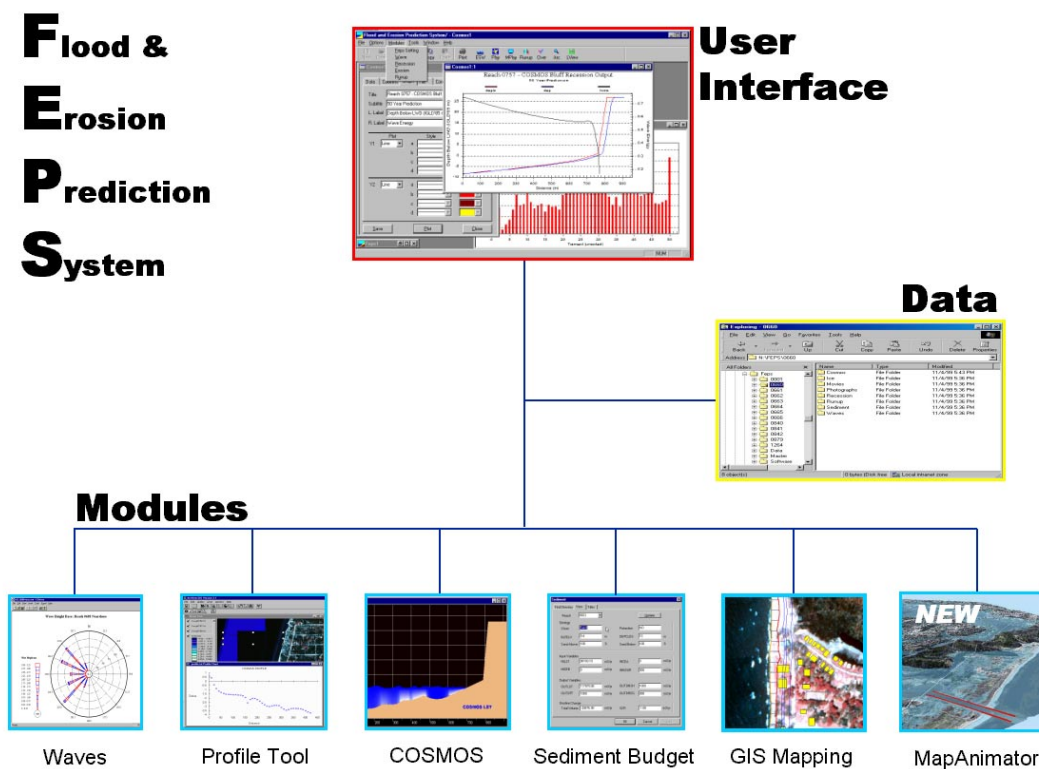


Figure 2.1 FEPS Interface and Modules

bottom of the diagram. Both the user interface and modules are linked to the coastal database.

The FEPS interface was coded with Microsoft Foundation Classes (MFC) Visual C++. The user interface presently includes over 60,000 lines of code and over 60 different dialog boxes. The modules in the FEPS have been coded in a variety of programming languages, including: MFC Visual C++, Fortran, and Avenue (ArcView's custom programming language).

## **2.2 FEPS Modules**

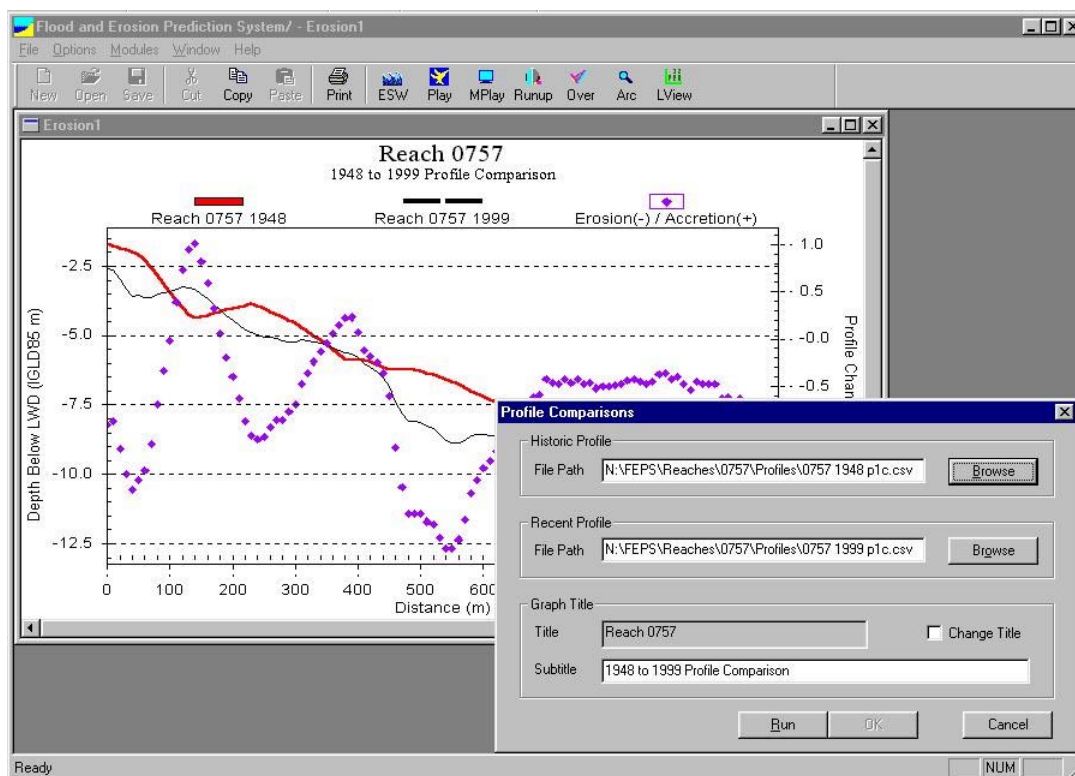
The individual modules of the FEPS developed by Baird & Associates are described, including: the user interface; the coastal database; the profile tool; ESWave; COSMOS longshore sediment transport estimates and cohesive shore erosion; the sediment budget module; a suite of ArcView applications known as the FEPS Shoretools; the runup and overtopping calculator; and MapAnimator for 3D Movie Maps.

### **2.2.1 *The User Interface***

The modules and data processing tools in the FEPS are accessed through the user interface noted in Figure 2.1. The FEPS interface is a dynamic visualization, plotting and data processing environment. The user can interact with several data sets simultaneously in multiple windows or views. Several of the capabilities of the user interface are highlighted below. The links to the various modules are discussed in further sections.

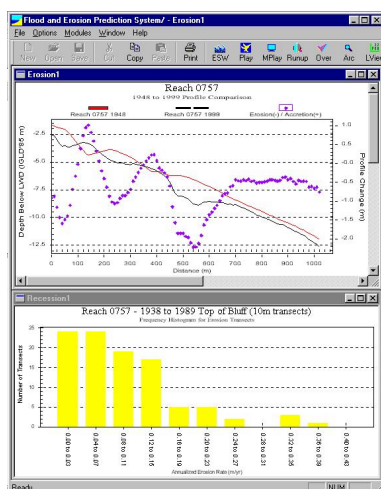
The Flood and Erosion Prediction System interacts with a wide variety of geo-spatial data sets and numerical model input/output. The diverse range of data must be visualized, processed, plotted and prepared for further analysis and model input quickly and efficiently. Existing commercial graphing software was not capable of interacting with the wide range of data in the FEPS, often required multiple importing steps (and input wizards), and was very time consuming.

Consequently, a series of plotting tools were developed for the user interface that could input, process and visualize the unique datasets generated with the FEPS. An example of a historic to recent profile comparison is provided in Figure 2.2. The user simply browses the system directory for the historic and recent profile data (i.e. XY coordinates in a CSV format), inputs a custom title as required, and the plot is generated. The plotting window allows for dynamic zooming capabilities and quick changes to line types and symbols. The plot can be saved in the coastal database for future reference, printed for report generation, or saved as a digital image.



**Figure 2.2 Custom Plotting Tools in the FEPS**

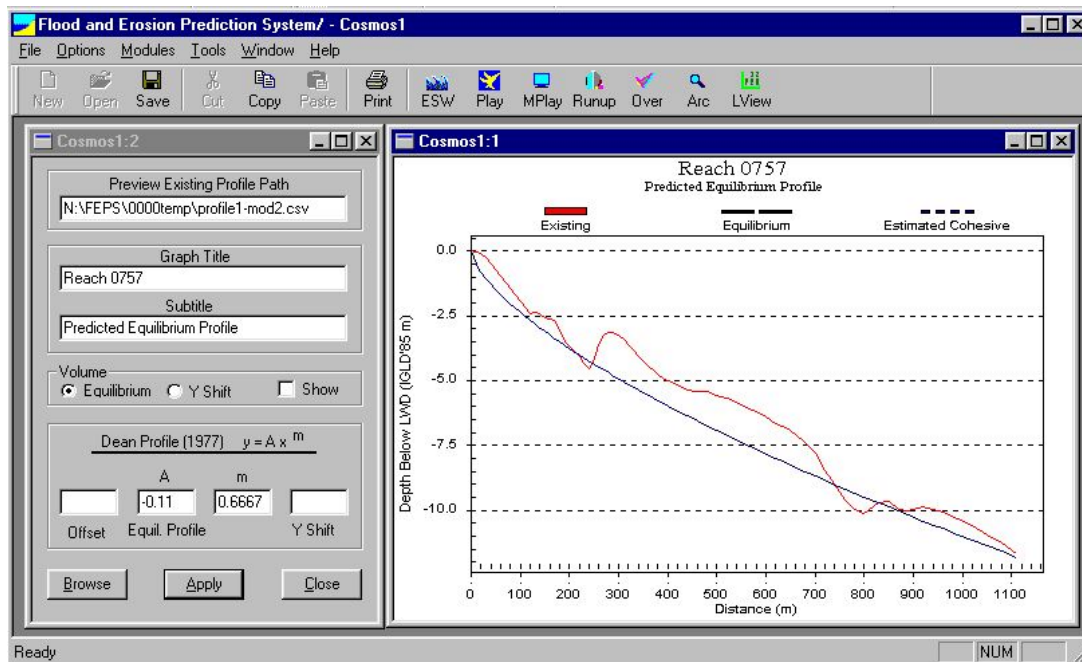
As mentioned above, the user interface can be used to process and visualize multiple spatial datasets simultaneously. For example, in addition to the profile comparison, the recession rate data for Reach 0757 is displayed simultaneously as a frequency histogram (along with many other graphs) in Figure 2.3. The multiple view capability can also be utilized to visualize data for different temporal scales at a given reach and from adjacent shoreline reaches.



**Figure 2.3 Multiple Graphs**

Many of the tools in the user interface are also used to process and prepare data extracted from the coastal database for numerical modeling of erosion and flooding hazards. For example, lake bed profiles extracted from the coastal database are utilized to generate input menus for the COSMOS model. However, prior to modeling cohesive shore erosion with the COSMOS model, the overlying sand deposits must be isolated and removed from the input profile geometry. This task was facilitated with the development of an interactive equilibrium profile tool based on Dean's equation (Dean, 1977). An example of the

tool is presented in Figure 2.4. The user queries the coastal database for an existing 2D



**Figure 2.4 Equilibrium Profile Tool**

lake bed profile, which is visualized in the plotting window. An equilibrium profile curve is fitted to the extracted profile based on the selected parameters in Dean's equation. The results are viewed interactively in the plotting window. Once an appropriate curve is selected, the results are saved in the coastal database for future model input.

### 2.2.2 The Coastal Database

The coastal database incorporates a wide range of geo-spatial information, including: point data such as lake level gages and dredging records; reach specific data such as the shoreline classification and the 1 km bluff mapping; and near continuous information such as existing lake bed bathymetry and ortho-photographs. Other key datasets include: wind wave hindcasts, ice cover time series, historic bathymetry and bluff mapping, beach nourishment records, sediment grain size, ground level photography and digital elevation models.

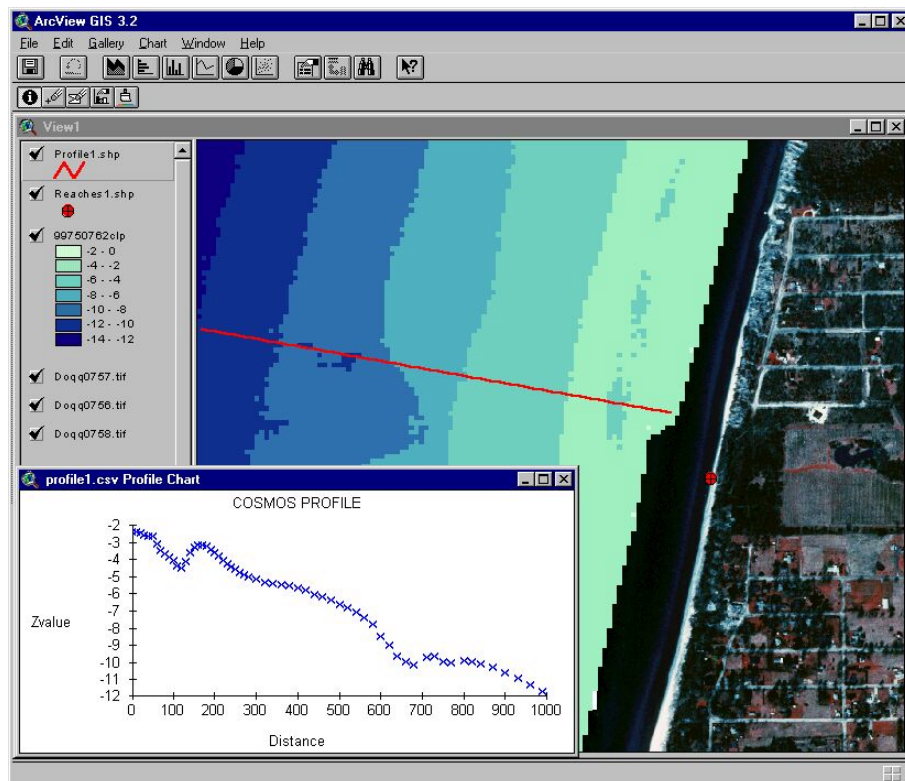
Presently, the data storage and file structure for the coastal database utilizes the root directory and folder structure in Windows Explorer (Figure 2.1). Reach specific information such as erosion estimates from COSMOS are stored in sub-directories for the individual reaches (i.e. >FEPS/reaches/0757/COSMOS). The coastal data utilized for the FEPS modeling presently resides on a dedicated server in the Baird Office.

In FY01, the benefits and disadvantages of incorporating a commercial database into the FEPS system will be investigated. Also, alternatives for the development of an internet based file server and online GIS mapping tools will be reviewed. Internet access to the spatial datasets and mapping results represent a potential vehicle to serve the project data and results to interested state and local governments, and the general public.

### 2.2.3 *Profile Tool and Bluff Slope*

The 2D coastal process model COSMOS is utilized in the FEPS to predict rates of longshore sediment transport, cross-shore storm related profile change for sandy sites, and cohesive shore erosion. One of the primary inputs is a 2D beach/lake bed profile with X-Z coordinates. Considering that multiple profiles are often required for each shoreline reach and the Lake Michigan shoreline has over 2,000 reaches, automated methods were required to extract the profile data from the 3D lake bed grids efficiently and accurately.

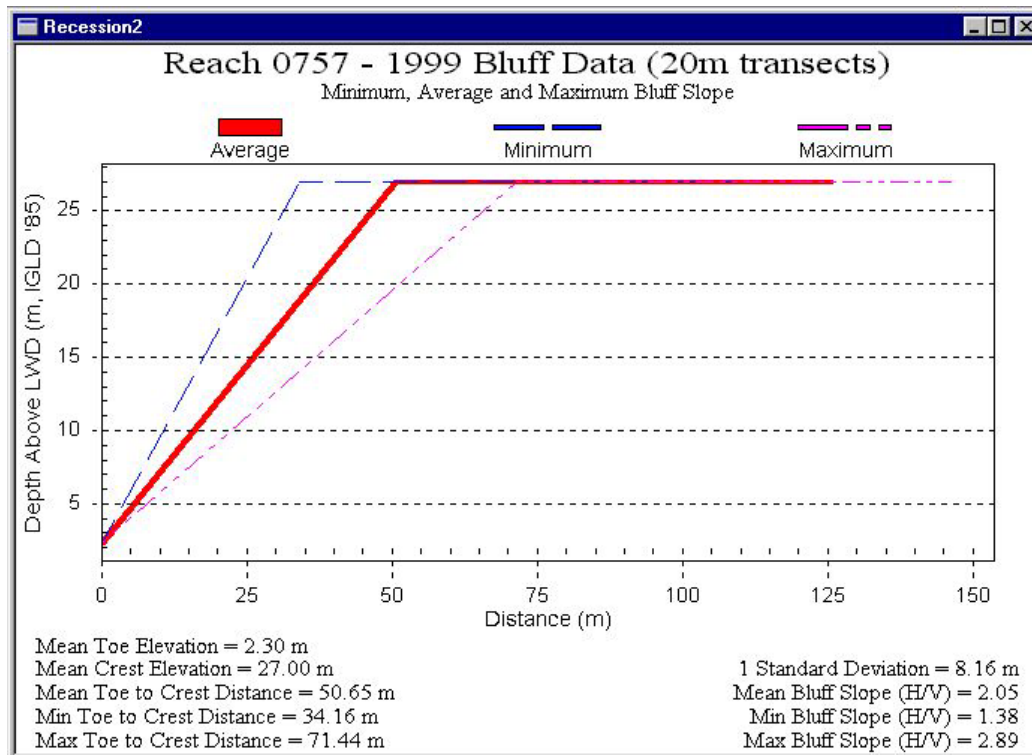
The FEPS Profile tool is a custom application developed within ESRI's ArcView workspace. To use the tool, it is necessary to have a 3D surface or grid of the nearshore bathymetry loaded as an active theme in ArcView. With the profile tool selected from the ArcView workspace, the user draws a line across the 3D bathymetry grid at the desired location, as seen in plan view in Figure 2.5. The tool extracts a digital X-Z profile,



**Figure 2.5 FEPS Profile Tool**

provides an on screen summary (graph in Figure 2.5), and saves the X-Z coordinates in a comma delimited ASCII file (in the coastal database).

The second step in the development of beach profiles for the shoreline reaches was the analysis of bluff and dune slope. The analysis and extraction of bluff slope data from the coastal database is discussed further in the Section 2.2.7. The FEPS interface is used to analyze and graph the data on bluff and dune slope for the 1 km shoreline reaches. Figure 2.6 provides an example of a bluff slope graph for Reach 0757, along with the summary



**Figure 2.6 Bluff Slope Graph and Statistics Calculated with the FEPS UI**

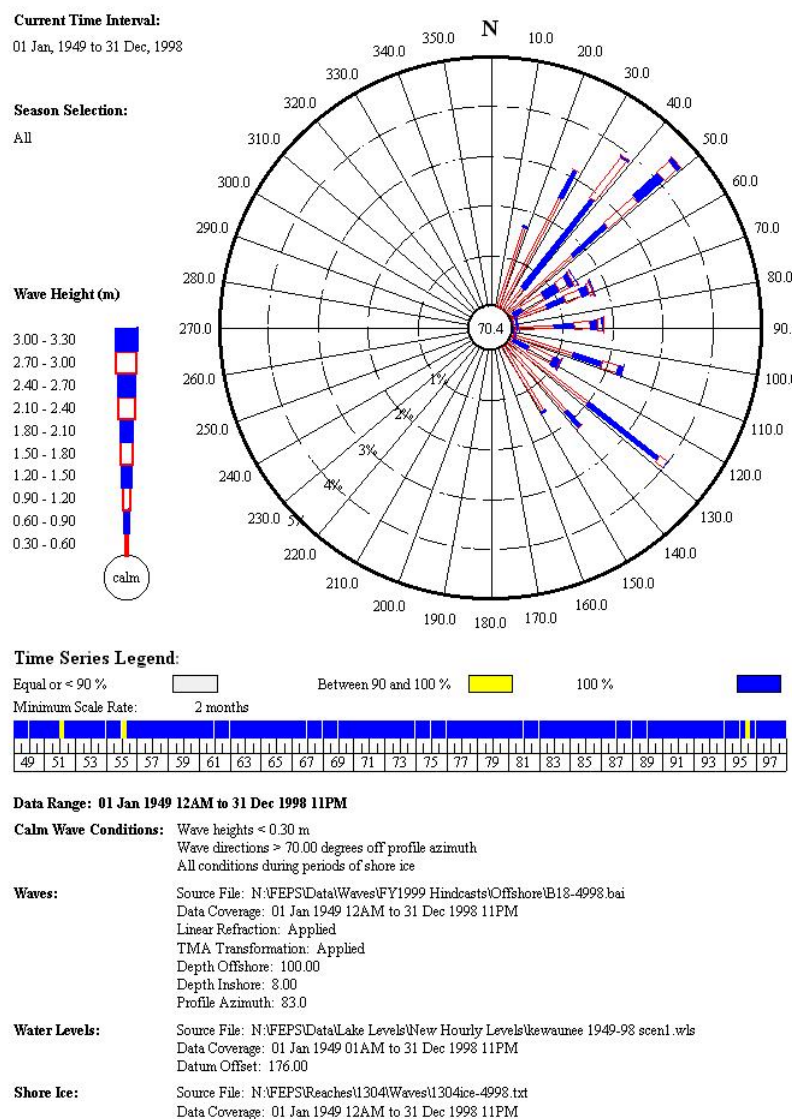
statistics at the bottom of the plot. Combined, the lake bed and bluff/dune slope data are used to generate 2D profiles for input to the COSMOS model.

## 2.2.4 ESWave Module

The ESWave module is a custom wave, lake level and ice analysis tool developed by Baird & Associates. The module performs numerous functions in the FEPS, including: creation of time series wave, lake level and ice data; visualization of the time series data in rose diagrams, splatter plots and summary tables; performing offshore to nearshore wave transformation; generation of storm summaries; calculation and export of monthly wave energy data; and export of time series files to run the COSMOS model (i.e. hourly wave, lake level and ice data).

In addition to the various methods to visualize the wave and lake level data in ESWave, the user has the ability to query only specified portions of the complete time series record. For example, the time scale can range from the entire dataset (i.e. 50 years), to one year or only a specified storm event (i.e. one day). The data analysis options can also be used to select a specific season, such as May to August, for visualization, analysis and exporting. For additional details on the ESWave module, refer to Baird's FY98 progress report (Baird, 1999).

A sample of a nearshore wave rose for Reach 1304 is presented in Figure 2.7. The graphic also includes a time series cover bar, the data range and digital metadata. The metadata provides a summary of all input files and user specified parameters for the wave transformation.

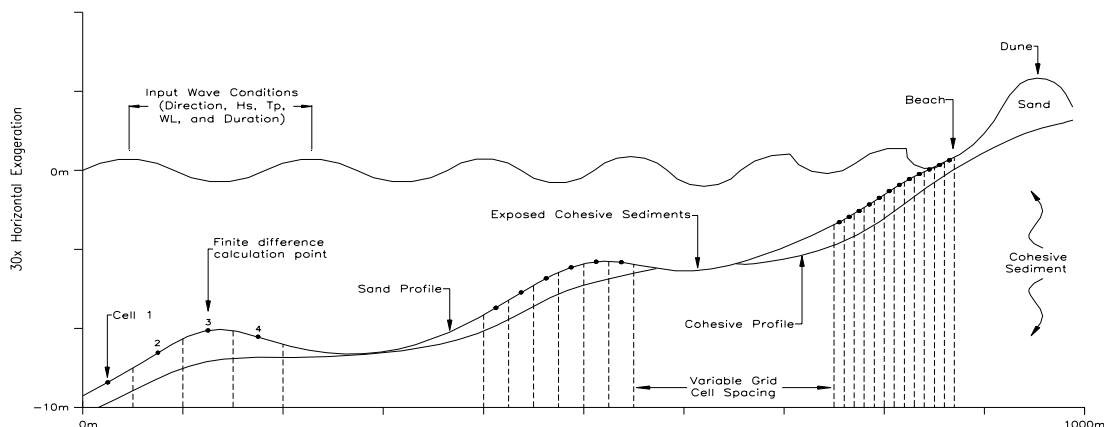


**Figure 2.7 Nearshore Wave Rose generated with ESWave**

### 2.2.5 COSMOS Model

COSMOS is a deterministic numerical model for the simulation of coastal processes. The 2D profile model consists of several predictive routines that describe the following parameters across a shore-perpendicular profile: random wave transformation (including refraction, bottom friction, shoaling, breaking, wave decay, runup, and overwash); steady currents (including undertow, and wave and tide-induced cross-shore and longshore currents); orbital velocities (linear and non-linear); suspended sediment distribution through the vertical; bed load and suspended load sediment transport in cross-shore and longshore directions; and 2D profile response due to gradients in cross-shore sand transport. For a detailed description of the model, refer to Nairn and Southgate (1993) and Southgate and Nairn (1993).

Each of the processes is evaluated at approximately 250 finite difference calculation points (or grid cells) across the profile, starting with the offshore limit and moving inshore. Refer to Figure 2.8 for a schematic description of the model input profile(s). In



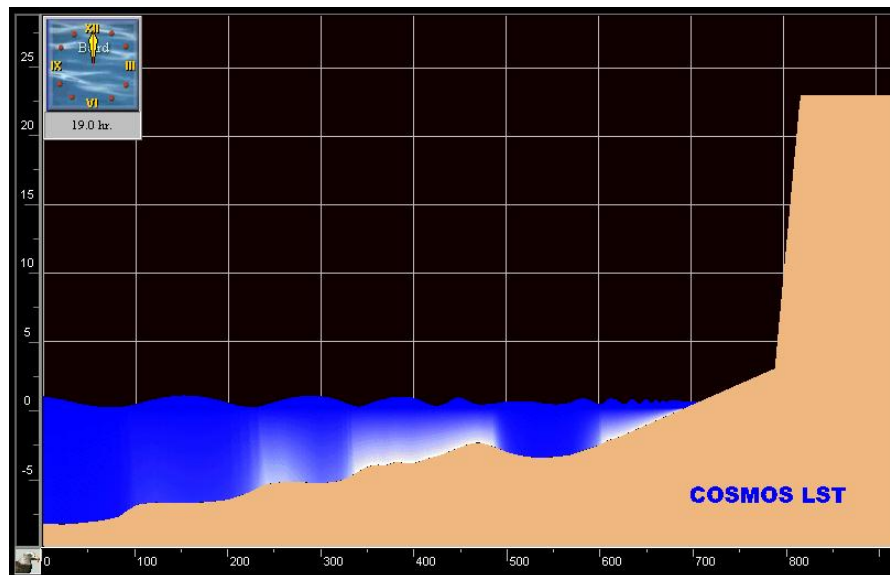
**Figure 2.8 COSMOS Inputs for a Profile with Cohesive Substrate and Sand Cover**

an independent review of cross-shore coastal models, Schoonees and Theron (1995) gave COSMOS (the Bailard version of the Energetics model) the highest possible rating.

Model inputs for estimates of longshore sediment transport, cross-shore sediment transport, cross-shore profile response and cohesive shore erosion include: 2D profile in x and z coordinates for the beach and lake bed profile (and cohesive sub-bottom profile, bedrock, and coastal structures if present); a shore perpendicular profile azimuth; description of the sediment grain size (including variability across the profile); and wave direction, height, period and water level on a hourly basis or in a statistical format.

### 2.2.5.1 COSMOS for Sandy Shorelines

For sandy coastlines, the model estimates are based on physical processes and there is no calibration required. For example, COSMOS is capable of predicting the magnitude and distribution across a profile of both longshore and cross-shore directed sediment transport for any sandy profile and wave / water level condition without calibration of coefficients. Figure 2.9 provides a graphical summary of the longshore sediment transport predictions for a multiple bar profile. The white shading indicates the magnitude and location of LST.



**Figure 2.9 COSMOS Longshore Sediment Transport Predictions**

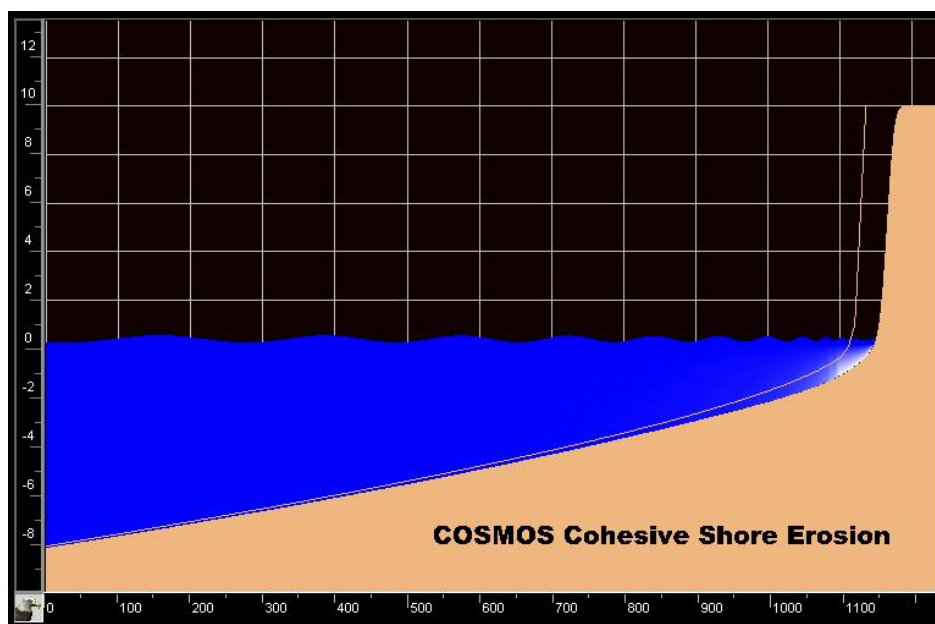
Two dimensional estimates of storm related profile response due to gradients in cross-shore transport are also calculated without calibration for the site specific profile geometry and sediment grain size. The profile grain size conditions can be specified as a single  $D_{50}$  value for the entire profile, or varied across the nearshore zone and beach based on the individual site conditions (i.e.  $D_{50}$  range from 0.1 to 5.0 mm).

Another unique capability of COSMOS is its ability to simulate supply-limited sand transport and beach erosion for sites which feature complex nearshore geologic patterns, such as exposures of consolidated cohesive sediment or bedrock, in addition to sand. At many locations on the Great Lakes, and elsewhere in the world, sand cover is only intermittent or exists as a relatively thin veneer above the underlying cohesive substrate. In addition to the input of a 2D sand profile to represent the surficial bed conditions, a second profile can be included in COSMOS to represent the cohesive substrate (either exposed or covered in a veneer of sand), as indicated in Figure 2.8. A third erosion resistant profile can also be used to represent exposures of non-erodible bedrock or coastal structures, such as revetments, seawalls, or offshore breakwaters.

#### 2.2.5.2 *COSMOS for Erosion of Cohesive Shorelines*

For cohesive shorelines, the COSMOS model is used in the FEPS to predict erosion of the nearshore lake bed and bluff for time scales ranging from years to several decades. Prior to calculating erosion, three erodibility coefficients must be calibrated in the model based on the geologic properties of the glacial sediments (i.e. resistance to the driving forces of erosion). In the absence of detailed geotechnical data for a site, the erodibility coefficients can be calibrated based on historic rates of erosion, such as lake bed downcutting rates and bluff retreat estimates.

An example of the model output is visualized in Figure 2.10. The single line represents the input profile and the solid orange is the output profile after 50 years of wave and lake



**Figure 2.10 COSMOS Cohesive Shore Erosion Estimate**

level time series data has been simulated in the model. In Figure 2.10, the rate of erosion or downcutting increases in an onshore direction and the bluff has retreated approximately 50 m in the simulation.

#### 2.2.6 *Sediment Budget Module*

A detailed sediment budget module was created for the FEPS. As Figure 2.1 indicates, the module is accessed through the user interface and is linked to the coastal database. There are two versions of the sediment budget module: 1) for sandy shore reaches where long term shoreline evolution is based on net changes in the sediment volume for the 1 km shoreline reaches; and 2) for cohesive reaches to investigate the interaction of

sediment input (sand and gravel) from bluff erosion and longshore sediment transport rates.

There are three primary input tabs, as illustrated in Figures 2.11a and b. The user specifies the title and reach boundaries in Figure 2.11a. The second tab in Figure 2.11b is used to browse the coastal database and identify key input parameters for the sediment budget, such as rates of longshore sediment transport, inputs from bluff erosion and beach nourishment. For all cases, the 1 km shore reaches define the spatial boundaries for each cell in the sediment budget. In the final tab, the user is able to visualize the results of the sediment budget for the various input and output variables on a reach by reach basis. The inputs extracted from the coastal database can be accepted or altered to test “what if” scenarios. For example, beach nourishment and dredging practices could be altered at a harbor to investigate the influence on the overall sediment budget. The net volume change is computed and converted to a shoreline change rate (i.e. m/yr) for the individual reaches. The results are also presented in a summary table for printing and report generation.

**Figure 2.11a Boundaries Tab**

**Figure 2.11b Sediment Budget Inputs from the Coastal Database**

### 2.2.7 FEPS “Shorettools”

A suite of custom ArcView GIS tools were developed to pre-process the geo-spatial data layers, extract data for input to the numerical models, automate manual tasks and map the future shoreline position. The four components of the FEPS “Shorettools” are described below. These tools were coded with the Avenue programming language to create custom input fields, link together a series of ArcView commands, automate manual routines, write files to the coastal database and map future shoreline position.

#### 2.2.7.1 Shore Splitter

The shoreline and bluff mapping for the prototype counties was delivered as continuous ArcView shapefiles (i.e. line coverages) for each of the five counties. However, the FEPS modeling was based on the 1 km shoreline reaches, which required reach specific bluff mapping, not county wide coverage. Since the geographic coordinates for the center point of the individual shoreline reaches was stored in the GIS, the Shore Splitter tool was developed to automate the task of creating the required 1 km bluff toe and top mapping in ArcView.

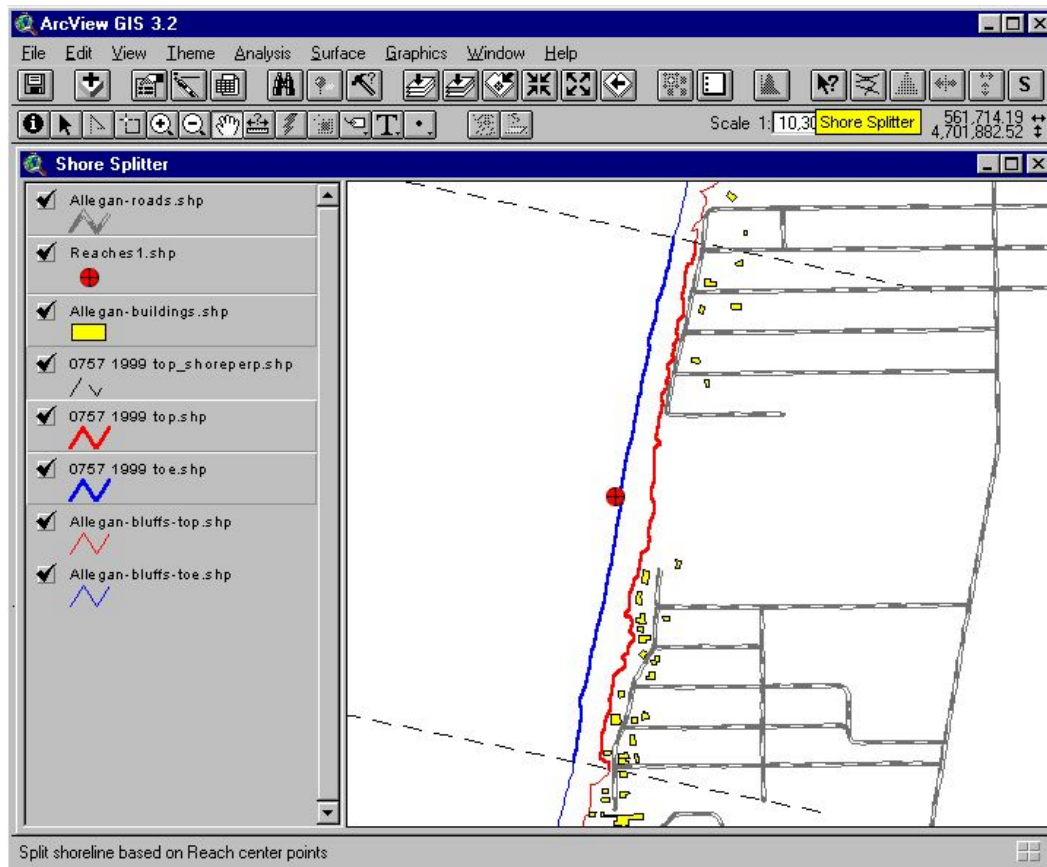


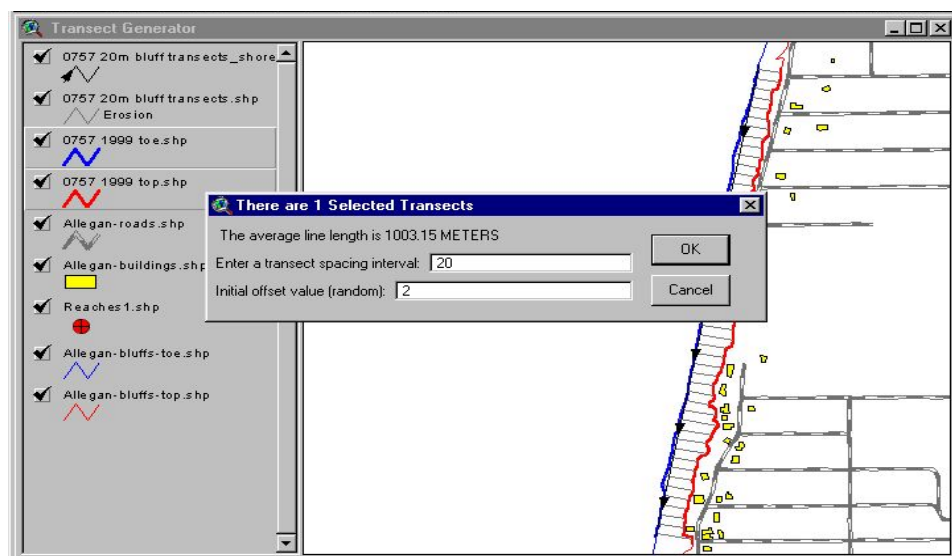
Figure 2.12 Shore Splitter Tool

An example of the end product from the tool is shown in Figure 2.12 for Reach 0757. The thin solid lines trending north south represent the county wide toe and top of bank lines. The dashed lines perpendicular to the shore represent the 1 km reach boundaries and are used to cut the new reach specific lines (thick lines in Figure 2.12). The Shore Splitter tools can also be used to create reach specific lines for the historic shoreline mapping.

#### 2.2.7.2 *Transect Generator (TG)*

The Transect Generator tool was also created with dual purpose: 1) to measure the horizontal distance between the bluff toe and crest lines in the GIS; and 2) measure transect erosion rates or shoreline change rates between two top of bank lines (or shorelines). The two methodologies are described in further detail below.

The toe and top of bank lines for the five prototype counties contained elevation data. In other words, the lines were three dimensional. This additional attribute information was utilized in the development of the Transect Generator tool to facilitate the calculation of bluff slope information for the individual reaches. Figure 2.13 presents the bluff toe and top of bank mapping for Reach 0757. A base line is drawn parallel to the general shoreline orientation with the tool and shore perpendicular transects are drawn from a random offset location along the baseline at a user specified spacing. TG creates a shape file with the new transects, and a comma delimited ASCII file which is stored in the coastal database. The raw ASCII file was used to create the bluff slope graph presented earlier in Figure 2.6.



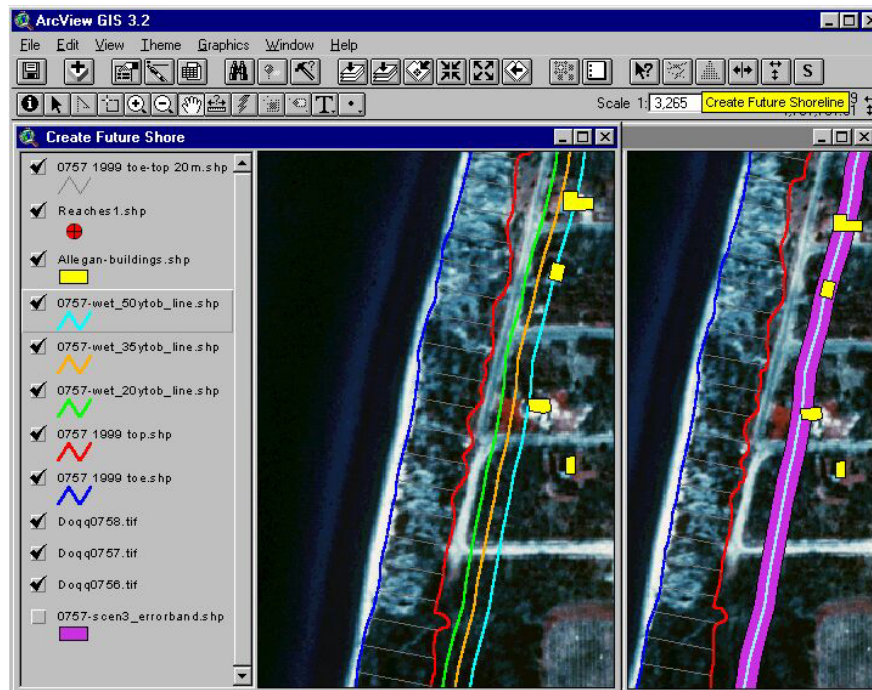
**Figure 2.13 Shore Perpendicular Transects from the TG Tool**

The ability to generate shore perpendicular transects with TG is also used to measure shoreline change rates between two shoreline positions. The methodology is similar to the description above for bluff slope, with the exception of extracting a 3D attribute from the shape files. The transects are stored in a shape file and an ASCII file is stored in the coastal database. The analysis and plotting tools in the FEPS are used calculate annualized erosion rates and generate graphs of shoreline change rates.

### 2.2.7.3 *Create Future Shoreline*

The estimates of future cohesive shoreline erosion under the LMPDS hydrological scenarios are completed with the COSMOS model for the individual 1 km shoreline reaches. These 2D modeling results are assumed to be representative of future erosion potential for the 1 km shoreline reach. The Create Future Shoreline tool was developed to map estimates of shore position for the cohesive reaches based on the COSMOS model predictions.

The tool relies on three files that the user generates and stores in the coastal database: 1) 1 km toe and top of bank mapping for the reaches; 2) analysis of bluff slope with TG and analysis functions in the User Interface; and 3) COSMOS model estimates at 20, 35 and 50 years (or other user selected intervals). Once the tool is launched from the ArcView desktop, the user is prompted to browse for the files from the coastal database for a particular reach. The end result is continuous mapping of the top of bank on a reach by reach basis at 20, 35 and 50 years in the future, as depicted in Figure 2.14. The second panel in the right hand portion of Figure 2.14 displays the 50 year future top



**Figure 2.14 Future Top of Bank Mapping**

of bank line, along with an uncertainty band (i.e. shaded polygon). The band was developed to account for uncertainty in future bluff slope within the reach, which has a direct impact on the location of the top of bank. The width of the uncertainty band is related to the variability of bluff slope within the 1 km reaches (refer to Section 5.2.1).

#### 2.2.7.4 Create Future Sandy Shoreline

Future shoreline position for the sandy reaches of Lake Michigan are determined with the sediment budget module in the FEPS. The end result from the sediment budget is an annualized shoreline change rate (SCR). The Create Future Sandy Shoreline tool was developed in ArcView to map future dune crest position based on the results of the sediment budget. Figure 2.15 presents the input form menu for the tool. The user specifies an appropriate file name, SCR and temporal scale (i.e. 20, 35, and 50 years), and the GIS automates the drawing of future dune crest lines. The future shorelines are saved as shapefiles in the coastal database.

The screenshot shows the ArcView GIS 3.2 interface. On the left, the 'View1' window displays a list of shapefiles: 'Grandhaven.sid', '0717 1999 toe.shp', '0717 1999 tob.shp', and '0717 1999 toe-tob 20m.shp'. The main window displays the 'Sandy Shorelines - Future Shore Tool - Baird and Associates' dialog box. The dialog box has the following fields:

- The current Transect Shapefile is:
- Output shapefiles will be placed in:

	Base Filename (*.SHP)	Shoreline Change Rate (erosion is positive)	Duration (yrs)	Uncertainty Band (Positive is landward)
1.	<input type="text" value="0717-scen1-20yr"/>	<input type="text" value="0.5"/>	<input type="text" value="20"/>	<input type="text" value="5.0"/>
2.	<input type="text" value="0717-scen1-35yr"/>	<input type="text" value="0.5"/>	<input type="text" value="35"/>	<input type="text" value="-5.0"/>
3.	<input type="text" value="0717-scen1-50yr"/>	<input type="text" value="0.5"/>	<input type="text" value="50"/>	<input type="text" value="5.0"/>

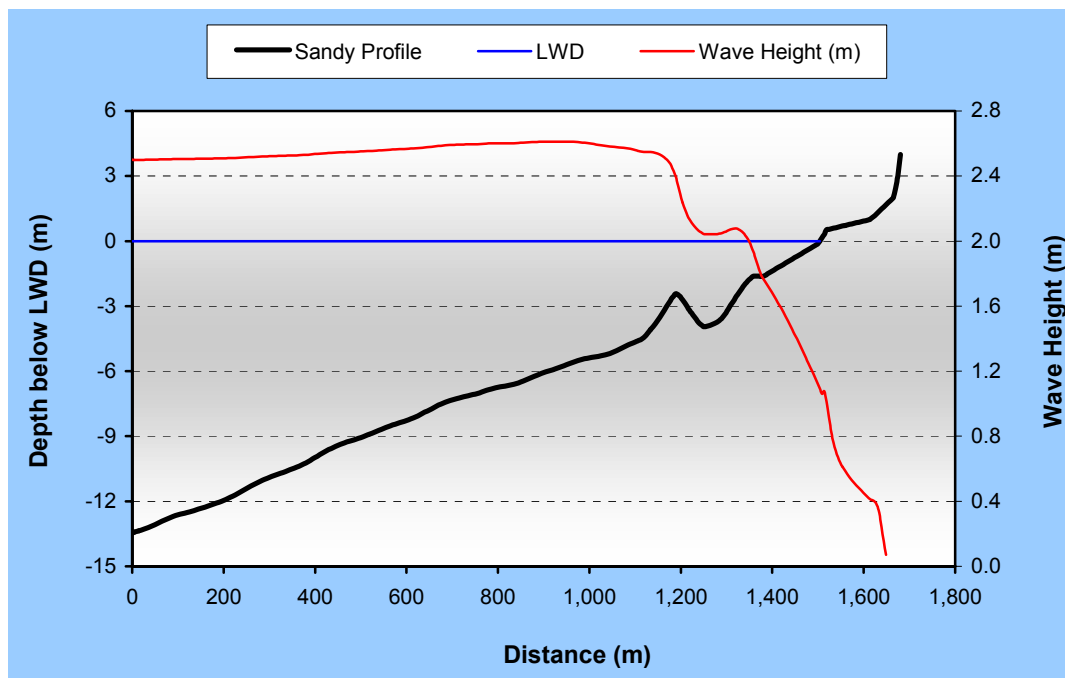
NOTE: All four fields for each scenario must be filled to calculate future shoreline.

Buttons: Cancel, OK

**Figure 2.15 Future Top of Bank Mapping**

### 2.2.8 Runup and Overtopping Calculator

To date, the flooding functionality in the system has not been extensively developed and integrated with the FEPS, especially in comparison to the erosion prediction tools. However, many of the physical processes related to wave attenuation, runup and overtopping can be simulated with the existing modules in the FEPS for open coast barrier beaches and dune areas. For example, ESWave is used to generate hourly time series data on wave height, lake level and ice cover. This hourly time series can then be input to the COSMOS model to predict wave attenuation from deep water to the beach. As Figure 2.16 demonstrates, the wave height can be determined for any hour in the 50 year time series record, at any location across the profile, for any reach on Lake Michigan that has the supporting data.



**Figure 2.16 COSMOS Estimate of Wave Height Attenuation**

The Runup and Overtopping Calculator is a module developed to predict rates of flooding and inundation for open coast sites, such as barrier systems and beaches. Imbedded in the calculator are numerous runup and overtopping equations which have common input criteria, such as wave height, period, slope, beach sediment characteristics and structure type. The inputs are entered by the user and stored in the table at the bottom of the calculator. Examples of estimates from the Runup and Overtopping calculator are provided in Figures 2.17 and 2.18.

**Runup Calculator**

Structure Type: Beach Type

Equation: Mase 1989  
Smooth, impermeable, 1:5~30  
Irregular Waves

Runup: 1.97 m

Variables:

Sig. Wave height,  $H_s$  (m): 2

Peak Wave Period,  $T_p$  (s): 7

Beach Type: Sand

Beach Slope, 1:x: 10

Depth at Toe (m): 0

Reduction Factor: 1.0

No.	R(m)	H(m)	T(s)	TYPE	SLOPE	DEPTH
1	1.24	2.00	7.00	Sand	10.00	0.00
2	1.55	2.00	7.00	Sand	10.00	0.00
3	1.97	2.00	7.00	Sand	10.00	0.00

☐ Always push to table

OK Cancel Help

**Figure 2.17 Runup Calculator**

**Overtopping Calculator**

Structure Type: Revetment

Equation: Goda

Variable: Ahrens & Heimbaugh  
Goda  
Owen

Wave Period,  $T_p$  (s): 8.0

Depth at toe (m): 1.0

Freeboard (m): 3.0

Approach Slope (1:X): 2

Oblique Wave Factor

Wave Angle (deg.): 1.1

☐ Default (=1.15)

Wind Factor

Wind Speed (m/s): 20

Runup (m): 17.129 Get ...

☐ Default (=1.0)

Q=0.021 (m<sup>3</sup>/s/m)

No.	Q(m <sup>3</sup> /s/m)	H(m)	T(s)	D.T.(m)	F.B.(m)	S.S
1	0.035	5.00	8	1.0	3.00	2.00
2	0.021	5.00	8	1.0	3.00	2.00

☐ Always push to table

OK Cancel Help

**Figure 2.18 Overtopping Calculator**

When time series data is run through the calculator, flooding volume estimates can be computed for storm events, or longer durations. With further development, the FEPS could predict hourly runup and overtopping rates and transform these volumes to inundation levels on a suitable digital elevation model in ArcView.

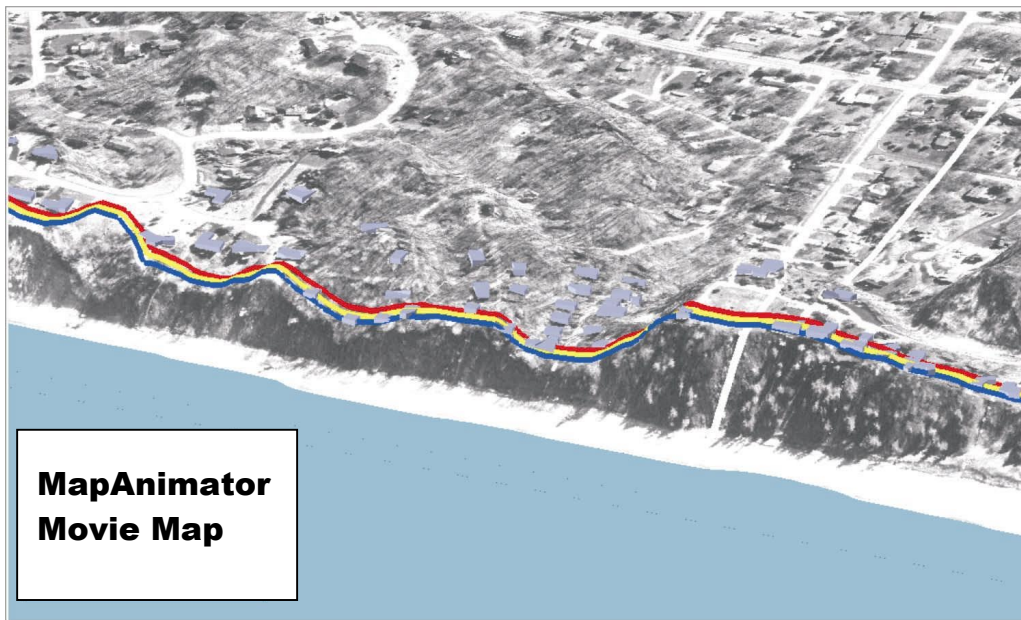
### 2.2.9 *MapAnimator 3D*

A recent addition to the Flood and Erosion Prediction System is 3D animation capabilities for the ArcGIS desktop suite of software (ESRI, Redlands, CA). MapAnimator can be accessed as a module to the FEPS and utilizes the 3D information in the coastal database. The module is used to create Movie Maps, the animated equivalent of a paper map with cartographic elements such as titles, legends and logos. A sample of the frames from a flooding movie are provided below in Figure 2.19.



**Figure 2.19** Sample frames of a flooding movie

The Movie Maps represent a powerful tool to communicate the results of the LMPDS to the study team, the general public and non-technical audiences. They are also a valuable tool at public meetings and can be distributed to coastal communities on Lake Michigan via the web. Figure 2.20 presents an example of a 3D scene north of the Holland jetties with the future top of bluff estimates from the FEPS (mapping at 20, 35 and 50 years).



**Figure 2.20** Future top of bluff mapping, north of Holland

### **3.0 COASTAL DATA AND THE SHORELINE CLASSIFICATION**

The Lake Michigan Potential Damages Study has and will continue to involve numerous comprehensive data collection initiatives (USACE, 2000). In many instances, the FEPS modules were utilized to transform, project, edit, and modify the original data for use in the study. The primary coastal datasets utilized in the FEPS will be presented, along with post-processing routines developed for the user interface.

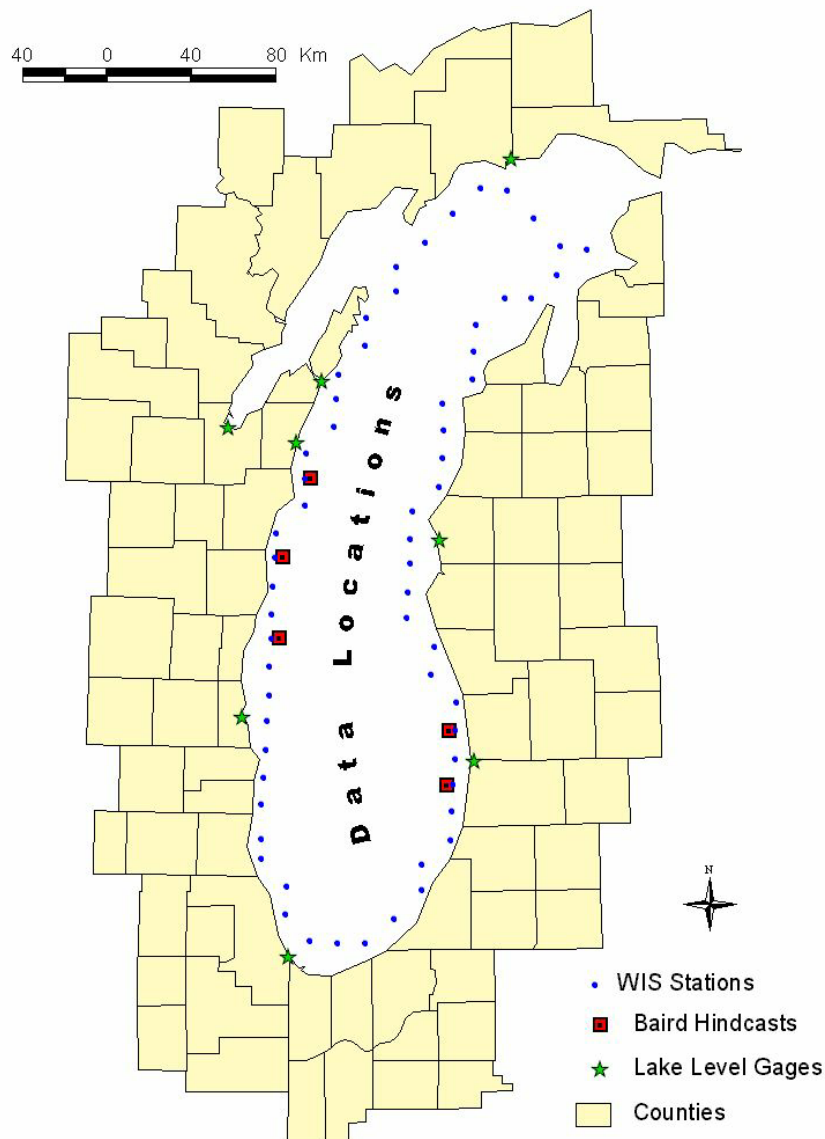
The Lake Michigan shoreline can be grouped into three broad categories which are characteristic of the Great Lakes Basin and include: sandy, cohesive and bedrock shores. These general shoreline types are based on the geologic properties of the shore materials and their response to the driving forces of erosion, such as wave energy and lake levels. Recognizing these three distinctive shore types and the corresponding erosion processes for sandy, cohesive and bedrock shorelines, a three tiered shoreline classification was developed for the 1 km reaches on Lake Michigan. The three tiers include: the shoreline stratigraphy above the waterline (geomorphic class), the lake bed surficial characteristics (sub-aqueous class) and the presence, type, and design life of shoreline protection structures (protection class). Examples of the classification are presented for Allegan County, along with a discussion of how it is used to select the modeling approach for the Flood and Erosion Prediction System.

#### **3.1 Coastal Data**

The primary coastal and geo-spatial datasets utilized in the FEPS to model future erosion response for the three LMPDS lake level scenarios are discussed, including waves, lake levels, ice cover, bathymetry, topography and historic recession rates. Graphic examples are provided.

##### **3.1.1 Waves**

The location of the WIS Stations for Lake Michigan are noted in Figure 3.1. The initial database extended from 1956 to 1987 (Hubertz et al., 1991) and was subsequently updated to include 1988 to 1997 for this study. As the Baird FY98 progress report has documented, substantial changes in the directionality and total wave energy were noted between the WIS data generated for the two periods (Baird, 1999). Consequently, Baird's 1D parametric hindcast model was used to complete five wind wave hindcast from 1956 to 1998 (43 years). The locations of the hindcasts correspond to the existing WIS Stations offshore of the five prototype counties and are noted in Figure 3.1.



**Figure 3.1 Location of WIS Stations, Baird Hindcasts and Lake Level Gages**

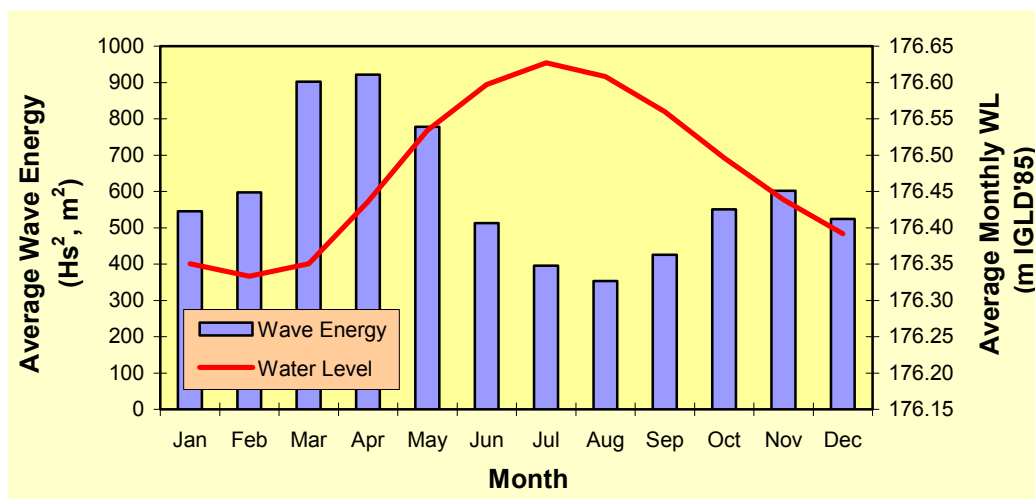
#### *3.1.1.1 Wave Energy and Lake Levels*

Meadows et al., 1997 have suggested a link between rising and falling lake levels and annual wave energy on the Great Lakes. Considering the findings of these studies, and the objective of developing a defensible wave climate to accompany the 50 year LMPDS lake level scenarios, a preliminary analysis of the relationship between lake level trends and wave energy was completed with hindcasted waves (Baird's software) centered on WIS Station 15 offshore of Sheboygan and on WIS Station 53 offshore of Grand Haven.

The ESWave module was utilized to evaluate wave energy for the time series record from 1956 to 1998. An estimate of deep water wave energy was calculated based on the square of the wave height for the duration of the time series, as follows:

$$E = \Sigma H^2$$

where  $E$  = estimated wave energy ( $\text{m}^2$ ) and  $H$  = wave height (m). The results are exported from ESWave on a monthly basis. A sample of the average monthly wave energy for Station 53 offshore of Grand Haven from 1956 through to 1996 is presented in Figure 3.2. The winter and late fall clearly represent the seasons of significant wave energy, with the summer corresponding to months of lower wave energy. The monthly mean water level for Lake Michigan is also included in Figure 3.2 to highlight the inverse relationship between wave energy and the seasonal fluctuations of lake levels.

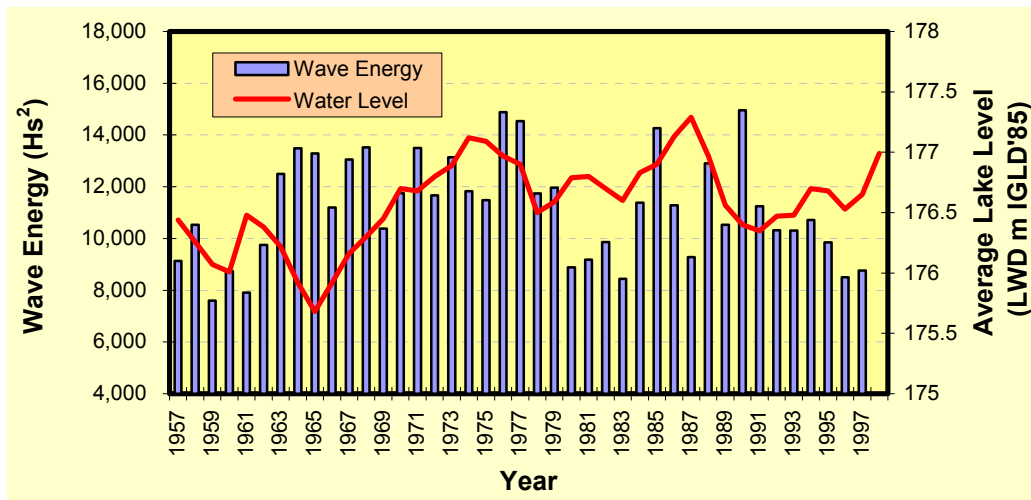


**Figure 3.2 Average Monthly Wave Energy, Baird Hindcast at WIS Station 53**

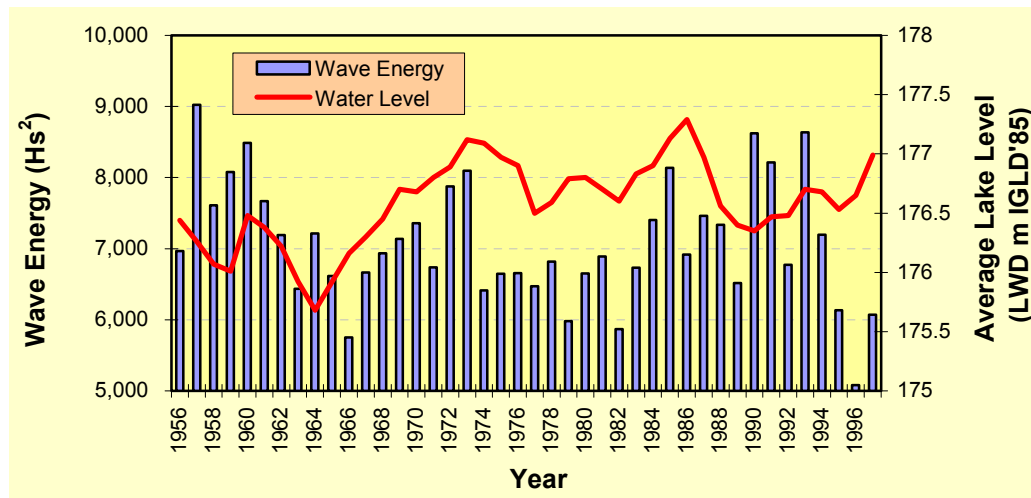
The annual wave energy estimates for Station 53 and the average yearly lake level from 1957 to 1996 is plotted in Figure 3.3. Based on a visual comparison, there does appear to be some trends between the cycles of annual wave energy and lake levels. For example, from the low lake levels recorded in 1965 to the peak in 1974, the annual wave energy was also generally increasing, especially when compared to the low annual energy values in the late 1950s and 1980s. From the late 1970s to the late 1980s there was a significant drop in annual wave energy and a corresponding decrease in lake levels.

The comparison of average yearly lake levels and annual wave energy at WIS Station 15 offshore of Sheboygan is presented in Figure 3.4. From 1960 to 1964 there appears to be a trend of reduced wave energy and falling lake levels. The opposite occurs from 1965 to 1973, when both wave energy and lake levels are steadily increasing. A drop in wave

energy from 1974 to 1984 also corresponded to a decrease in annual lake levels. From 1990 to 1997 there does not appear to be any trend in lake levels and annual wave energy.



**Figure 3.3 Annual Wave Energy vs. Average Yearly Lake Level (Baird Hindcast at WIS Station 53, offshore of Grand Haven, Ottawa County, MI)**



**Figure 3.4 Annual Wave Energy vs. Average Yearly Lake Level (Baird Hindcast at WIS Station 15, offshore of Sheboygan, Sheboygan County, WI)**

In summary, it should first be noted that a rigorous statistical analysis was not completed to identify trends between wave energy and lake levels. Nonetheless, the plotting comparisons of annual wave energy and yearly lake levels did identify several decades where the trends in lake levels and wave energy appeared to correspond. However, there was also other segments of the historical time series where no relationship was observed. In general, the relationship was stronger for the hindcasted waves at WIS Station 15 offshore of Sheboygan (Figure 3.4), when compared to the hindcasted waves at WIS

Station 53 (Figure 3.3) on the east side of the lake. One possible explanation is the prevailing south westerlies associated with high pressure systems on Lake Michigan that consistently generate smaller waves that propagate towards the eastern shores of Lake Michigan. The fact that the magnitude of wave energy is almost double at Station 53 when compared to Station 15 also supports this observation. Wave energy associated with the smaller waves mask the signal generated by severe storm events generally from the east, northeast and northwest which are related to precipitation events in the basin, and thus changes in lake levels.

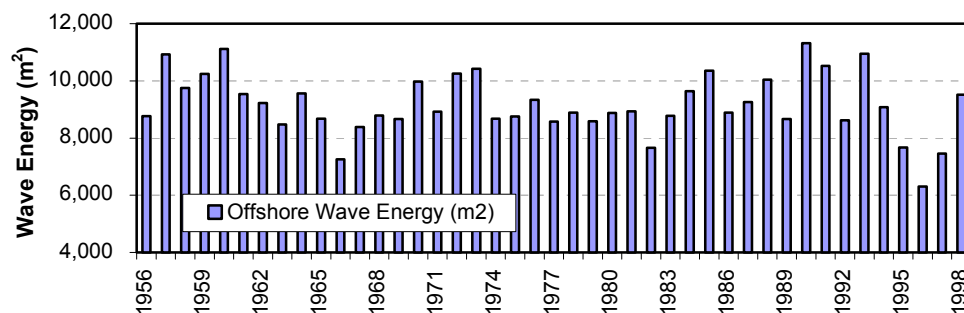
One of the primary objectives of the LMPDS was to quantify the magnitude of potential erosion damages associated with different future hydrological scenarios (i.e. lake level effects). Therefore, although the preliminary analysis identified some correlation between lake levels and wave energy trends, further research on this topic has not been pursued at this time. Consequently, the same 50 year wave climate was combined with each of the three LMPDS lake level scenarios for the modeling. This decision is discussed further in the latter sections of the report.

### 3.1.1.2 Generation of a 50 Year Wave Time Series

The temporal scale for the future hydrological scenarios generated by GLERL was 50 years. However, the length of the Baird wind wave hindcast was ~43 years at the WIS Stations. Therefore, a defensible approach was required to extend the 43 year wave time series to 50 years to match the duration of the LMPDS lake levels.

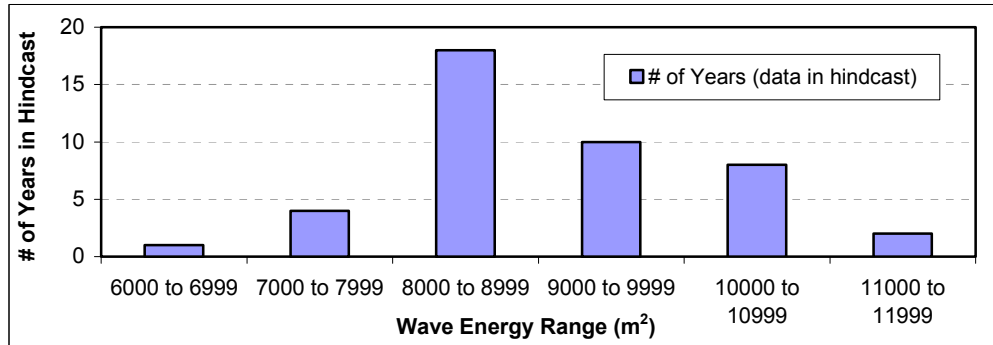
A methodology was developed to extend the wave time series based on the statistical distribution of wave energy from 1956 to 1998. The steps are described below for the Baird hindcast data at WIS Station 12:

1. The ESWave module was used to export the annual wave energy from the existing 43 year Baird hindcast at WIS Station 12, as described above. The annual deep water wave energy at Station 12 offshore of Ozaukee County is presented in Figure 3.5;



**Figure 3.5 Annual Deep Water Wave Energy Offshore Ozaukee Co. (WIS #15)**

2. A histogram, based on wave energy bins of 1,000 m<sup>2</sup>, was used to plot the population distribution of annual wave energy. The results are presented in an offshore wave energy histogram in Figure 3.6a;



**Figure 3.6a Wave Energy Histogram, Ozaukee Co. (WIS #15)**

3. The number of years for each wave energy bin and the corresponding percent occurrence for the 43 year record is listed in the Percent Occurrence Table (Figure 3.6b). In order to

determine the distribution for 7 new representative years, the percent occurrence for each wave energy bin was multiplied by 7 years. The approximate yearly distribution is listed in the final column of the table in Figure 3.6b;

Wave Energy (m <sup>2</sup> )	# of Years (hindcast)	% Years	Distribution for 7 Years	Approx. Yearly Distribution
6000 to 6999	1	2.3%	0.2	
7000 to 7999	4	9.3%	0.7	1
8000 to 8999	18	41.9%	2.9	3
9000 to 9999	10	23.3%	1.6	2
10000 to 10999	8	18.6%	1.3	1
11000 to 11999	2	4.7%	0.3	
Total Years	43	100%	6.8	7

**Figure 3.6b Percent Occurrence Table (WIS #15)**

4. Based on the approximate distribution in the table, 7 representative years of historic data were selected based on annual wave energy. For example, three years were required with a wave energy of 8,000 to 8,999 m<sup>2</sup>. The three years selected are highlighted in Figure 3.6c (1967, 1956, and 1978);

Year (sorted)	Energy per Year
1996	6309
1966	7253
1997	7461
1982	7657
1995	7668
1967	8391
1963	8471
1977	8579
1979	8590
1992	8626
1989	8668
1969	8671
1965	8680
1974	8681
1975	8759
1956	8766
1983	8781
1968	8789
1980	8877
1978	8889
1986	8893

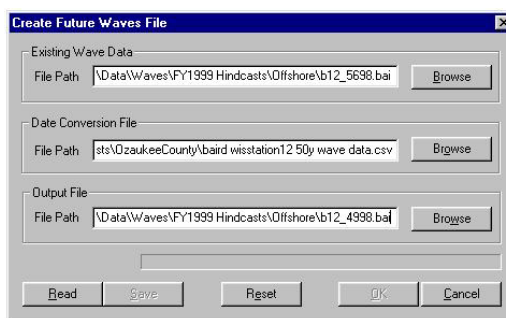
**Figure 3.6c**

5. Figure 3.6d lists the extended 50 year wave dataset based on steps 1 through 4. From 1949 to 1955 the wave data was selected from the actual record based on the statistical distribution of wave energy. From 1956 to 1998, the actual wave data was utilized;
6. Once the pairings were developed for the data extension (i.e. 1949-1955), a digital time series file was generated with a custom tool that was developed in the FEPS user interface. The data input window to create the new 50 year wave time series file is presented in Figure 3.7. The user selects the existing wave file, a date conversion file (i.e. for data extension date pairs in Table 3.6d), and an output file name.

NEW 50 Year Data Set	ACTUAL DATA for Yearly Waves	
1949	1966	↑ statistical selection ↓
1950	1967	
1951	1956	
1952	1978	
1953	1987	
1954	1984	
1955	1993	
1956	1956	↑ actual ↓
1957	1957	
1958	1958	
1959	1959	
1960	1960	
1961	1961	
1962	1962	
1963	1963	
1964	1964	
1965	1965	
1966	1966	
1967	1967	
1968	1968	
1969	1969	
1970	1970	
1971	1971	
1972	1972	
1973	1973	
1974	1974	
1975	1975	
1976	1976	
1977	1977	
1978	1978	
1979	1979	
1980	1980	
1981	1981	
1982	1982	
1983	1983	
1984	1984	
1985	1985	
1986	1986	
1987	1987	
1988	1988	
1989	1989	
1990	1990	
1991	1991	
1992	1992	
1993	1993	
1994	1994	
1995	1995	
1996	1996	
1997	1997	
1998	1998	

**Figure 3.6d**

The methodology of extending the wave data to 50 years was followed for each of the five Baird wave hindcasts noted in Figure 3.1. The methodology described above was followed for the remaining 4 hindcasts.



**Figure 3.7 Create Future Wave File Tool**

### 3.1.2 Recorded Lake Levels and LMPDS Scenarios

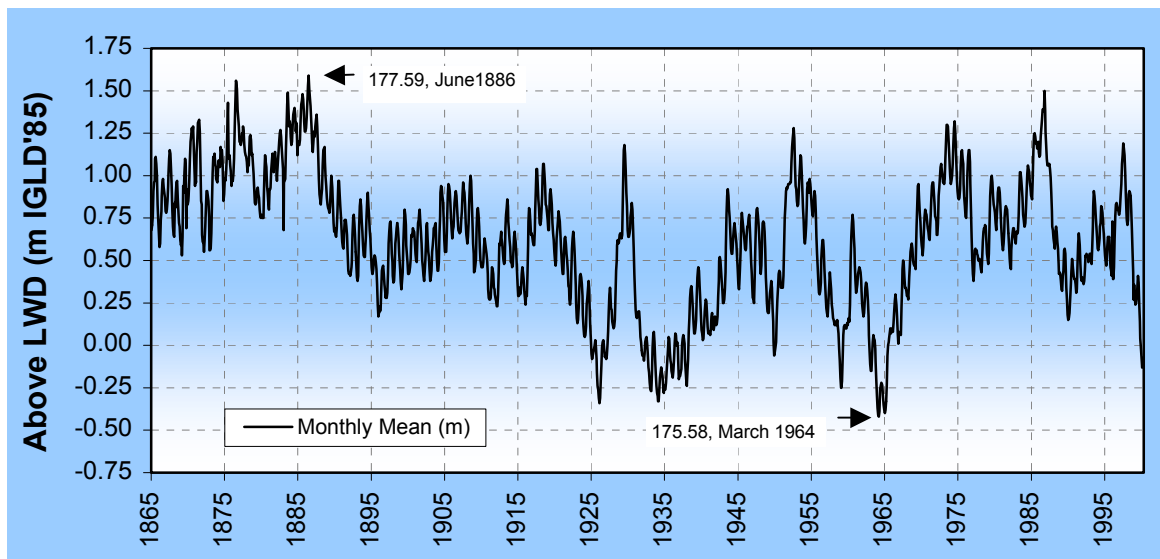
The coastal database contains several types of lake level data for Lake Michigan, including long term monthly mean levels representative of the entire lake, hourly gage data for several stations, and the estimated future levels based on the hydrological scenarios developed by GLERL. The lake level data and a post processing tool developed

in the UI is used to create the hourly 50 year time series files for the modeling as described below.

### 3.1.2.1 Recorded Monthly Means – Long Term

Long term monthly mean lake levels were obtained from the Detroit District USACE. The historic digital record extends from the 1865 to present and is summarized in Figure 3.8. The long term range in monthly levels for Lake Michigan is approximately 2.0 m, with a high of 177.59 m above CD recorded in June, 1886 and a low of 175.58 m in 1964.

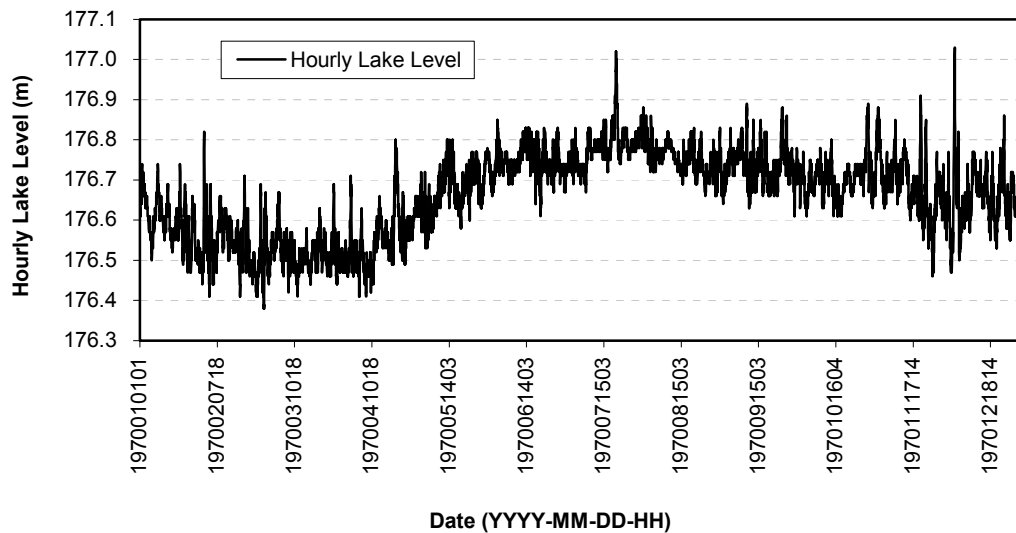
The recorded historic lake level information was used during the calibration of the erodibility coefficients in the COSMOS model for cohesive shore erosion estimates and to evaluate historic erosion rates generated from various temporal periods.



**Figure 3.8 Lake Michigan Monthly Means**

### 3.1.2.2 Hourly Gage Data

Digital hourly water level data for Lake Michigan was available at a total of 8 gages round the lake from 1970 to present. The locations of the gages are provided in Figure 3.1. Historic gage data prior to 1970 is not available in a digital format. An example of the hourly lake level data at the Holland gage (#908731) in 1970 is provided in Figure 3.9. The data captures the seasonal trend of rising levels in the spring and short term surges related to storm events.



**Figure 3.9 1970 Hourly Lake Levels at the Holland Gage (908731)**

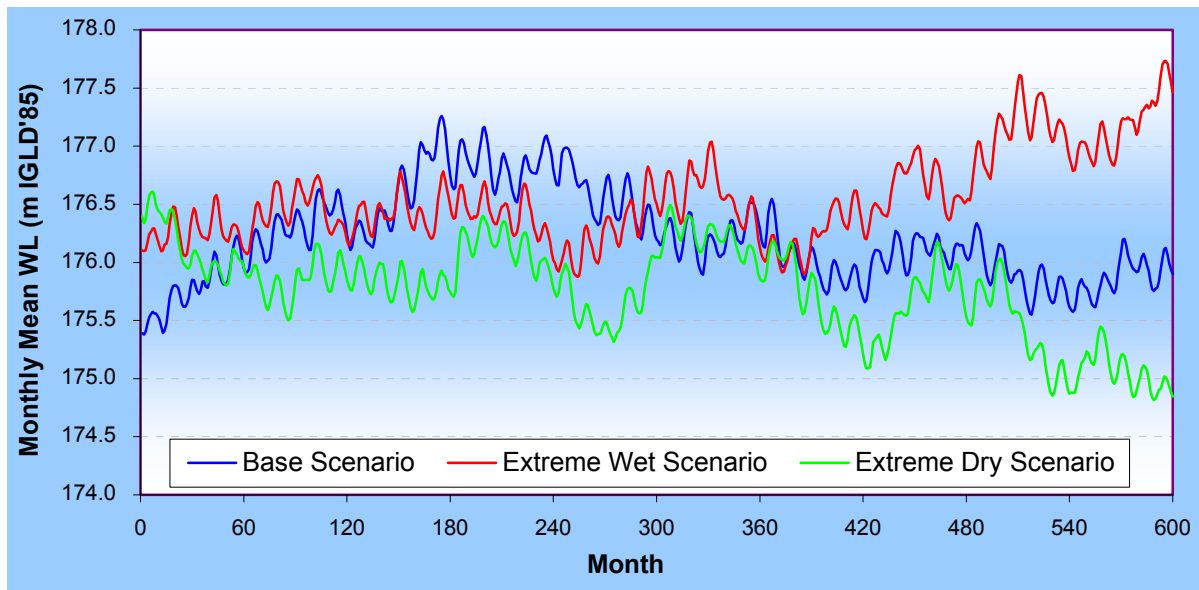
### 3.1.2.3 LMPDS Future Lake Level Scenarios

The Great Lakes Environmental Research Laboratory (GLERL) was contracted to prepare a series of future hydrological scenarios based on water supply sequences for the Great Lakes Basin. The ultimate product was a 50 year time series of monthly lake levels for each sequence. Five of the alternative hydrological scenarios were selected for detailed study in the LMPDS. Refer to USACE (2000) for additional details.

Of the five alternative scenarios generated by GLERL, three were selected for the detailed FEPS modeling and are referred to as the ‘LMPDS lake level scenarios.’ The three LMPDS scenarios are summarized below:

1. Base Case (similar wet/dry years and mixture of high and low lake levels);
2. Extreme Wet (more wet years and thus higher lake levels);
3. Extreme Dry (more dry years and thus lower lake levels).

The monthly means for the three LMPDS lake level scenarios are presented in Figure 3.10. Since the scenario data only provide a single monthly mean, water level fluctuations due to storm surge and wind setup are not incorporated in the database. Another important observation is that the extreme high and low levels for the extreme wet and dry scenarios occur near the end of the 50 year time series record. For the first 20 years (months 1 to 240), there is less separation in the monthly means between the three scenarios.

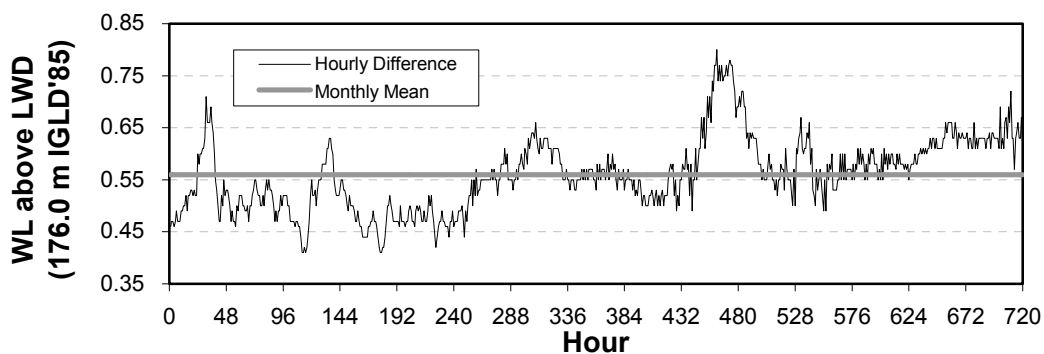


**Figure 3.10 Fifty Year LMPDS Lake Level Scenarios**

#### 3.1.2.4 Hourly Difference Levels from Gage Data

The erosion and sediment transport modeling with the COSMOS model requires hourly wave, water level and ice coverage data. However, as mentioned, the LMPDS future scenarios were only monthly means (Figure 3.10), and did not include short term level changes due to storm surges and wind setup. Consequently, a methodology was required to generate hourly level differences from the monthly mean based on storm surge effects.

For the period of record at the individual gages (~1970 to present), monthly means were calculated from the hourly time series data. The monthly mean was then subtracted from the actual hourly value to determine the hourly difference from the mean (i.e. referred to as the 'hourly difference level'). An example of the hourly difference level for the month of April, 1970 at Holland is provided in Figure 3.11. The monthly mean, 0.56 m above



**Figure 3.11 Monthly Mean and Hourly Difference Level (April 1970, Holland Gage)**

LWD, is plotted as the straight gray line and the hourly difference level is the thin black line that fluctuates within a 0.4 m range during the month of April. A time series hourly difference level file from 1970 to 1998 was created for the three gages utilized in the prototype investigations.

As discussed in Section 3.1.2.3, the temporal scale for the erosion analysis in the FEPS was 50 years. However, the recorded gage data with complete coverage was only available from ~1970 to 1997 (at the time of database development), as noted in Table 3.1 for the Holland gage (column I). For the period 1949 to 1969, and 1998 there was no recorded gage data available (column II). Two methodologies were developed to extend the hourly difference level data to the required 50 year temporal scale based on the relationship between wave energy and surge. Method One was developed for the years 1949 to 1955 and is described in the four steps below:

1. Hourly difference levels were not available from 1949-1955, as noted in Step 1, column XI;
2. The wave data for 1949 was based on the 1997 hindcasted waves, as discussed in Section 3.1.1.2 (Step 2 in columns IV and V);
3. Hourly difference levels were available for 1997, which corresponds to the year of wave data used to create the 1949 waves (Step 3 in column X);
4. The 1997 hourly difference levels were selected to be combined with the LMPDS lake level scenarios in 1949 (Step 4 in column XII). The Method One procedure, as outlined in steps 1 through 4 in Table 3.1, was followed for the remaining years to fill the gap of missing data from 1950 to 1955.

Method Two was developed for the years of missing hourly gage data from 1956 to 1969, plus 1998. Steps A to E are outlined below:

1. Hourly difference levels were not available from 1956 to 1969, as noted in Step A, column XI;
2. The annual wave energy for the hindcasted 1956 waves is noted in Step B, column VII;
3. In Step C, the 1956 wave energy is located in column IX;
4. Since there is no recorded lake level gage data in 1956, a year with hourly difference levels and the closest value for annual wave energy was selected. For 1956, the year with the closest total wave energy that also has hourly difference levels, was 1998, as noted by Step D in column IX;

5. The hourly difference levels for 1998 are selected for the 1956 levels in the extended dataset, as noted in Step E, column XII. The Method Two procedure was followed for the remaining years to 1969, plus 1998 as noted in Table 3.1.

**Table 3.1**  
**Data and Methods to Create a 50 Year Hourly Difference Lake Level File (Holland Gage)**

HOURLY DATA		WAVE DATA			WAVE ENERGY		WAVE ENERGY SORTED		DATA FOR 50 YEAR RECORD		
Actual Gage Data (I)	Missing Data (II)	Actual Wave Data (III)	Missing Data (IV)	Years used for Data Extension (V)	Year (VI)	Wave Energy per Year (VII)	Year (sorted) (VIII)	Wave Energy per Year (IX)	Actual Hourly Diff. Levels (X)	Missing Data (XI)	Years used for Data Extension (XII)
	1949		1949	2 1997					1 1949	4 1997	
	1950		1950	1987					1950	1987	
	1951		1951	1989					1951	1989	
	1952		1952	1986					1952	1986	
	1953		1953	1978					1953	1978	
	1954		1954	1971					1954	1971	
	1955		1955	1977					1955	1977	
	1956	1956			1956	B 7365	1959	7301	A 1956	E 1998	
	1957	1957			1957	9030	1956	C 7365	1957	1981	
	1958	1958			1958	10151	1961	7665	1958	1995	
	1959	1959			1959	7301	1960	8343	1959	1998	
	1960	1960			1960	8343	1998	D 8491	1960	1998	
	1961	1961			1961	7665	1997	8553	1961	1998	
	1962	1962			1962	9682	1983	8594	1962	1982	
	1963	1963			1963	12530	1996	8765	1963	1988	
	1964	1964			1964	13360	1980	8860	1964	1971	
	1965	1965			1965	13740	1981	8958	1965	1985	
	1966	1966			1966	11646	1957	9030	1966	1979	
	1967	1967			1967	12890	1982	9632	1967	1988	
	1968	1968			1968	13652	1962	9682	1968	1971	
	1969	1969			1969	10665	1987	9716	1969	1993	
1970		1970			1970	11509	1995	9832	1970		
1971		1971			1971	13233	1958	10151	1971		
1972		1972			1972	11772	1989	10510	1972		
1973		1973			1973	13137	1993	10600	1973		
1974		1974			1974	11265	1969	10665	1974		
1975		1975			1975	11161	1994	10908	1975		
1976		1976			1976	14428	1992	11119	1976		
1977		1977			1977	14384	1975	11161	1977		
1978		1978			1978	11638	1986	11181	1978		
1979		1979			1979	11655	1991	11184	1979		
1980		1980			1980	8860	1974	11265	1980		
1981		1981			1981	8958	1984	11459	1981		
1982		1982			1982	9632	1970	11509	1982		
1983		1983			1983	8594	1978	11638	1983		
1984		1984			1984	11459	1966	11646	1984		
1985		1985			1985	14225	1979	11655	1985		
1986		1986			1986	11181	1972	11772	1986		
1987		1987			1987	9716	1963	12530	1987		
1988		1988			1988	12839	1988	12839	1988		
1989		1989			1989	10510	1967	12890	1989		
1990		1990			1990	14536	1973	13137	1990		
1991		1991			1991	11184	1971	13233	1991		
1992		1992			1992	11119	1964	13360	1992		
1993		1993			1993	10600	1968	13652	1993		
1994		1994			1994	10908	1965	13740	1994		
1995		1995			1995	9832	1985	14225	1995		
1996		1996			1996	8765	1977	14384	1996		
1997		1997			1997	8553	1976	14428	3 1997		
	1998	1998			1998	8491	1990	14536		1998	1997

Method One

1 to 3

Method Two

A to E

Actual Hourly Difference Levels

Method Two

Based on the combined approach of Method One and Two, the historic record of hourly difference levels was extended to create a 50 year sequence of hourly time series difference levels for the period 1949 to 1998.

### 3.1.2.5 'Create Future WLS' Tool

The LMPDS monthly means and the extended hourly difference levels for the Holland gage were summarized in Table 3.1. The table also outlines the temporal scale of the wave data for Ottawa and Allegan Counties.

A custom tool was developed in the UI to combine the 50 year LMPDS means with the hourly difference levels calculated and extended for the individual gages. The input window is presented in Figure 3.12. The following steps are followed to generate a new 50 year hourly lake level file that combines the LMPDS monthly means and the hourly difference levels:

1. Browse the FEPS coastal database for a monthly lake level file for one of the three LMPDS scenarios (i.e. scen3.out). The 'Data Range' field is auto-populated based on the temporal limits of the data in the selected file (i.e. grayed boxes). The user must then specify the duration of data to extract from the 100 record (i.e. 50 years) and the start year (i.e. 1925);
2. The hourly difference level file for the appropriate gage must then be selected (i.e. Holland.out). The duration of the hourly difference level data is provided in the 'Data Range' fields (i.e. 1970 Jan,1 to 1998 Jun,30);
3. The 'Convert Record File' is a manually generated ASCII file that extends the duration of the hourly difference levels based on the methods outlined in Section 3.1.2.4 and Table 3.1. When the existing hourly difference levels for a particular year are copied to extend the data, the "copied from" and "to" dates are scanned by the software to check for discrepancies due to leap years. The dates are corrected automatically;
4. The user then selects a file name and directory for the storage of the new 50 year hourly LMPDS lake level file with surge (i.e. Holland 1949-98 scenario3.wls – the extreme wet scenario).

The methodology described above for the Create Future WLS tool was followed for all of the gages utilized in the investigations at the prototype counties and for the three LMPDS Scenarios.

**Figure 3.12 Create Future Water Level Tool**

### 3.1.3 Ice Cover for Lake Michigan

The formation of ice cover on the Great Lakes is controlled by several key processes, including: ambient air temperature, lake water temperature, lake depth (i.e. heat storage) and surface motion (Assel, 1995; Assel, 1996). For investigations of coastal erosion, presence or absence of ice cover has several key implications: 1) on a lake wide basis, the development of ice sheets (either continuous or patchy) will affect the propagation and growth of deep water waves; 2) the growth of shoreline ice will protect lake bed and bluff from the wave erosive; and 3) ice can scour the lake bed and shoreline.

The methodology to create a historic ice cover time series dataset for Lake Michigan was described in Baird (1999). In summary, the weekly ice charts for the lake were reviewed and the extent of ice cover was recorded as it corresponded to the 1 km shoreline reaches. Based on the extent and temporal duration of the coverage, a time series record was created for the entire lake from 1973 to 1998.

As with the wave and lake level data, the existing time series record was not of sufficient duration to combine with the 50 year LMPDS monthly mean lake levels (i.e. only 26 years of data). Consequently, a defensible approach was required to extend the 1973 - 1998 data to a 50 year time series. Since air temperature is a critical factor affecting ice formation (both water and ambient), one potential approach was to investigate the links between temperature and the LMPDS future hydrological scenarios. In this manor, the amount of ice cover would vary between the three lake level scenarios used for the numerical modeling. However, temperature was not a variable considered in the future hydrologic scenarios and this approach was not pursued.

Since links between climatic variables and the LMPDS scenarios were not investigated, ice cover and annual wave energy were compared at one reach in each of the prototype counties to look for potential patterns. An example is provided for Reach 0728 in Figure 3.13. No trends or patterns were observed between annual wave energy and ice cover for Reach 0728 or in the remaining counties. Consequently, in the absence of any climatic variables to guide the data extension, the time series record from 1973 to 1998 was

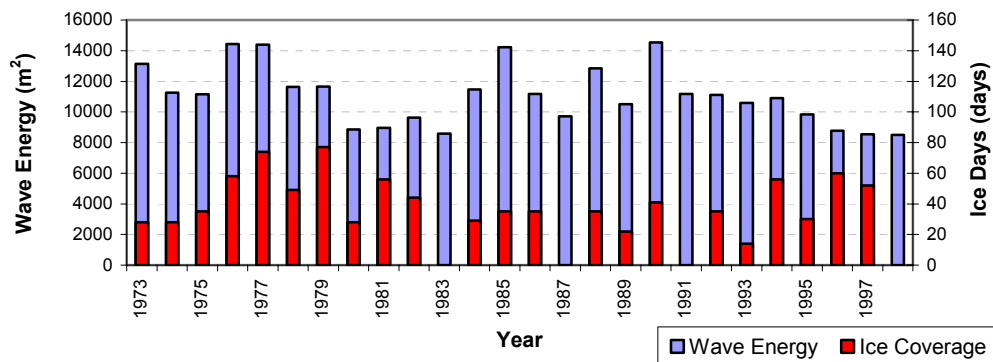


Figure 3.13 Offshore Wave Energy vs. Ice Cover Days (WIS # 55, Reach 0728 ice)

simply assumed to be representative of the 1949 to 1972 period of missing data. Also, the identical ice climate was used for all three LMPDS lake level scenarios selected for the detailed modeling. There was no attempt to account for potential temperature differences between the future scenarios and thus influence on ice cover.

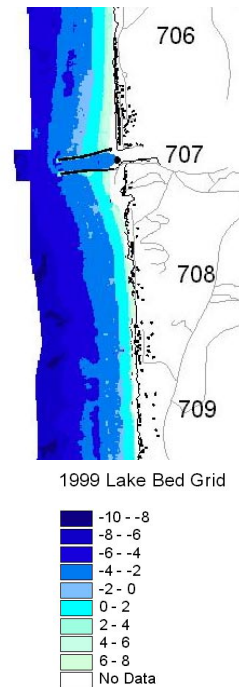
The ‘Create Future Ice File’ tool was developed for the UI and used to extend the existing ice time series data to 50 years. The input fields are presented in Figure 3.14.

**Figure 3.14** Input Fields for the Create Future Ice File Tool

### 3.1.4 Bathymetry

High resolution current bathymetric data is a necessity for the application of the FEPS. Without recent bathymetry, there is no reliable data to extract 2D profiles for the reaches that is representative of the present site conditions. For example, prior to the LMPDS the most recent county wide bathymetric data was 1948 NOAA survey data in the Michigan prototype counties. In Wisconsin, the only county wide bathymetry available was NOAA survey data from 1913.

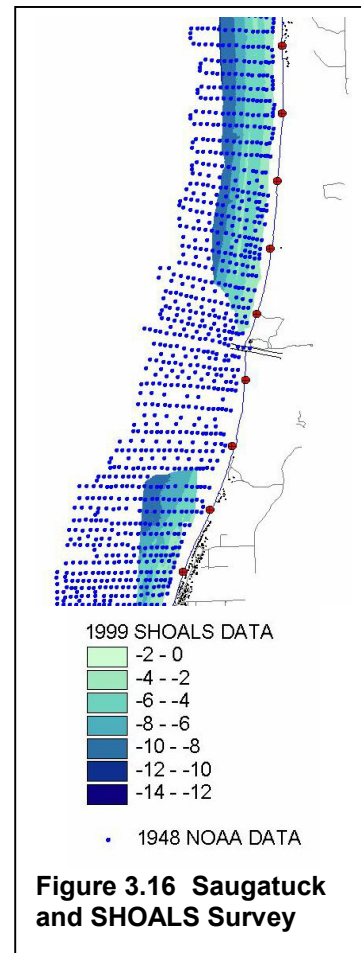
In the fall of 1999 a SHOALS survey was completed for the three Wisconsin prototype counties and the Michigan counties of Ottawa and Allegan. A sample of the 3D bathymetric grid generated in ArcView GIS from the SHOALS data is presented in Figure 3.15.



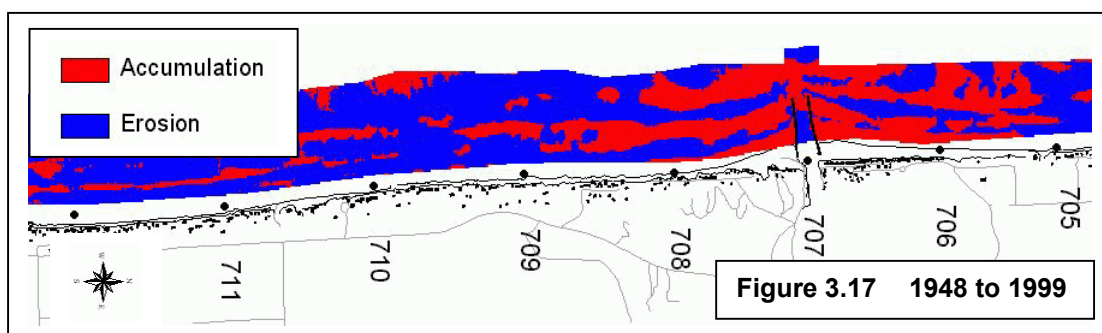
**Figure 3.15**

In several locations in Allegan and Ottawa Counties, the SHOALS coverage did not provide sufficient data coverage. For example, in the vicinity of the Saugatuck Harbor piers, there was no SHOALS data coverage for approximately 2 km (Figure 3.16). For reference, the soundings for the historic 1948 NOAA survey are also noted on Figure 3.16. In cases where there were data gaps, the 1948 NOAA survey was used to generate profiles. In Wisconsin, the SHOALS survey was not successful in collecting bathymetric soundings of the lake bed due to wave activity and water clarity problems. Consequently, the 1913 NOAA lake bed survey was used for the investigations in the three Wisconsin prototype counties.

Although the historic bathymetric surveys available from NOAA were not ideal for generating a representative 2D profile for the numerical modeling, they do provide a valuable snap-shot of the historic lake bed conditions. The 3D grid of the SHOALS data at Port Sheldon, presented in Figure 3.15, provided data for a historic to recent bathymetry comparison. Figure 3.17 identifies areas of lake bed erosion and sedimentation north and south of the harbor jetties at Port Sheldon. ArcView GIS was also used to calculate volumetric changes between 1948 and 1999, which are required for the sediment budget module in the FEPS.



**Figure 3.16 Saugatuck and SHOALS Survey**



**Figure 3.17 1948 to 1999**

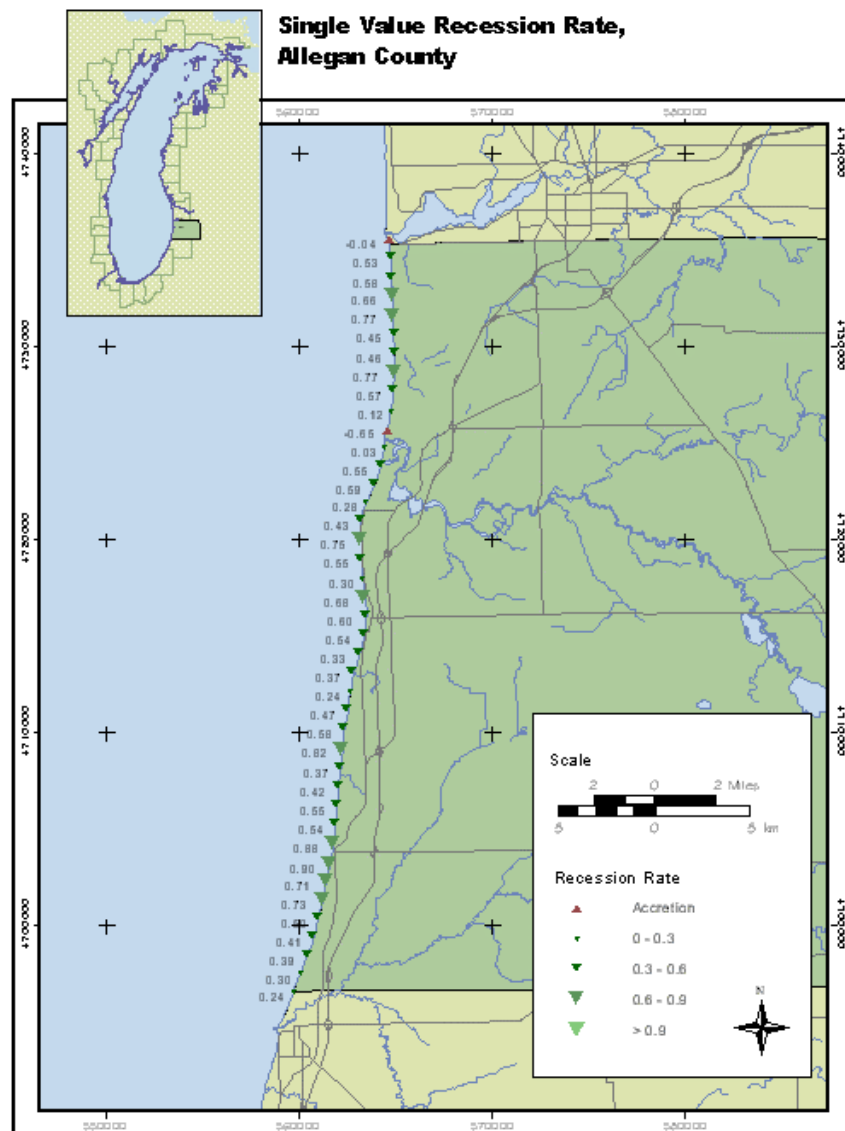
### 3.1.5 1999 Topographic Data

Detailed topographic data sets were generated from the 1999 aerial photography for the five prototype counties. The key topographic features utilized in the FEPS analysis were the toe and top of bluff mapping, buildings, roads, and coastal structures. A sample of the

bluff mapping, buildings, roads and coastal structures at Port Sheldon was provided in Figure 3.17.

### 3.1.6 *Single Value Recession Rates*

A literature review search of published recession rates was completed for the entire Lake Michigan shoreline (Stewart, 1997). Erosion rate data from previous studies was included in the shoreline classification based on the limits of the 1 km shoreline reaches. For each shoreline reach, one representative recession rate was selected from the published data. The selected rates for the 1 km reaches in Allegan County are presented graphically in Figure 3.18.



**Figure 3.18 Single Value Recession Rates for Allegan County**

An example of the available data for Reach 1172 in southern Ozaukee County, Wisconsin is listed in Table 3.2 to highlight the limitations of comparing recession rate data from various temporal scales, sampling density and different investigations. In total, nine mean recession rates were calculated in previous studies for Reach 1172, and the results ranged from 0.04 to 0.5 m/yr. It is important to note that the temporal scale for the recession rate data varied from 20 to 149 years, the actual number of measurements for the Reach varied from 1 to 13 transects (per 1 km), and the confidence in the rates ranged from 2 to 4 (with 1 being high). In the case of reach 1172, the 1963 to 1995 SEWRPC rate of 0.5 m/yr was selected. Issues regarding the use of published historic recession rates for the Lake Michigan Potential Damages Study are discussed further in Section 5.0 of the report.

**Table 3.2**  
**Sample of Recession Rates in the Classification for Reach 1172, Southern Ozaukee County, WI**

Reach (Km#)	Mean Recession Rate (m/yr)	# of Samples	Years of Record	Data Type	Confidence	Remarks / Source
1172	0.50	2	32	1	2	1963-1995 SEWRPC (1997)
1172	0.37	2	25	1	2	1970-1995 SEWRPC (1997)
1172	0.30	1	149	1	3	1836-1985
1172	0.04	1	143	1	3	1833-1976 Buckler (1981); Buckler and Winters (1983)
1172	0.06	1	108	1	3	1836-1944 Report of Committee (1945)
1172	0.06	1	100	1	4	1875-1975 APPROX Wisconsin CZM (Mickelson et al., 1977)
1172	0.11	13	39	1	3	1956-1995 SEH and Baker 1997
1172	0.12	4	22	4	2	1963-1985
1172	0.15	2	20	1	2	1975-1995 SEWRPC (1997)

### 3.2 Lake Michigan Shoreline Classification

The Lake Michigan shoreline was divided into 1 km shoreline reaches for the International Joint Commissions Levels Reference Study in the early 1990s (Nairn, 1992). The shoreline classification was subsequently reviewed in FY98 as a task in the LMPDS (USACE, 1999). For each 1 km of shoreline, the three tiered classification system was updated to categorize the shoreline stratigraphy above the waterline (geomorphic tier), the lake bed surficial characteristics (nearshore tier), the presence, type, and design life of shoreline protection structures (shore protection tier), and the volume of sand cover in the nearshore. A summary of geomorphic classification for the 2,436 1 km shoreline reaches on Lake Michigan is provided in Table 3.3.

**Table 3.3**  
**Summary of 1 km Shoreline Classification for Lake Michigan**

Shoreline Type	Number of 1 km Shoreline Reaches	Percentage of Lake Michigan Shoreline
Coastal Bluffs	398	16.3%
Low Banks	365	15.0%
Baymouth Barrier	90	3.7%
Sandy / Coarse Beaches	903	37.1%
Bedrock	376	15.4%
Open Shoreline Wetlands	105	4.3%
Artificial	199	8.2%
	2436	100.0%

### **3.2.1     *Geomorphic Tier***

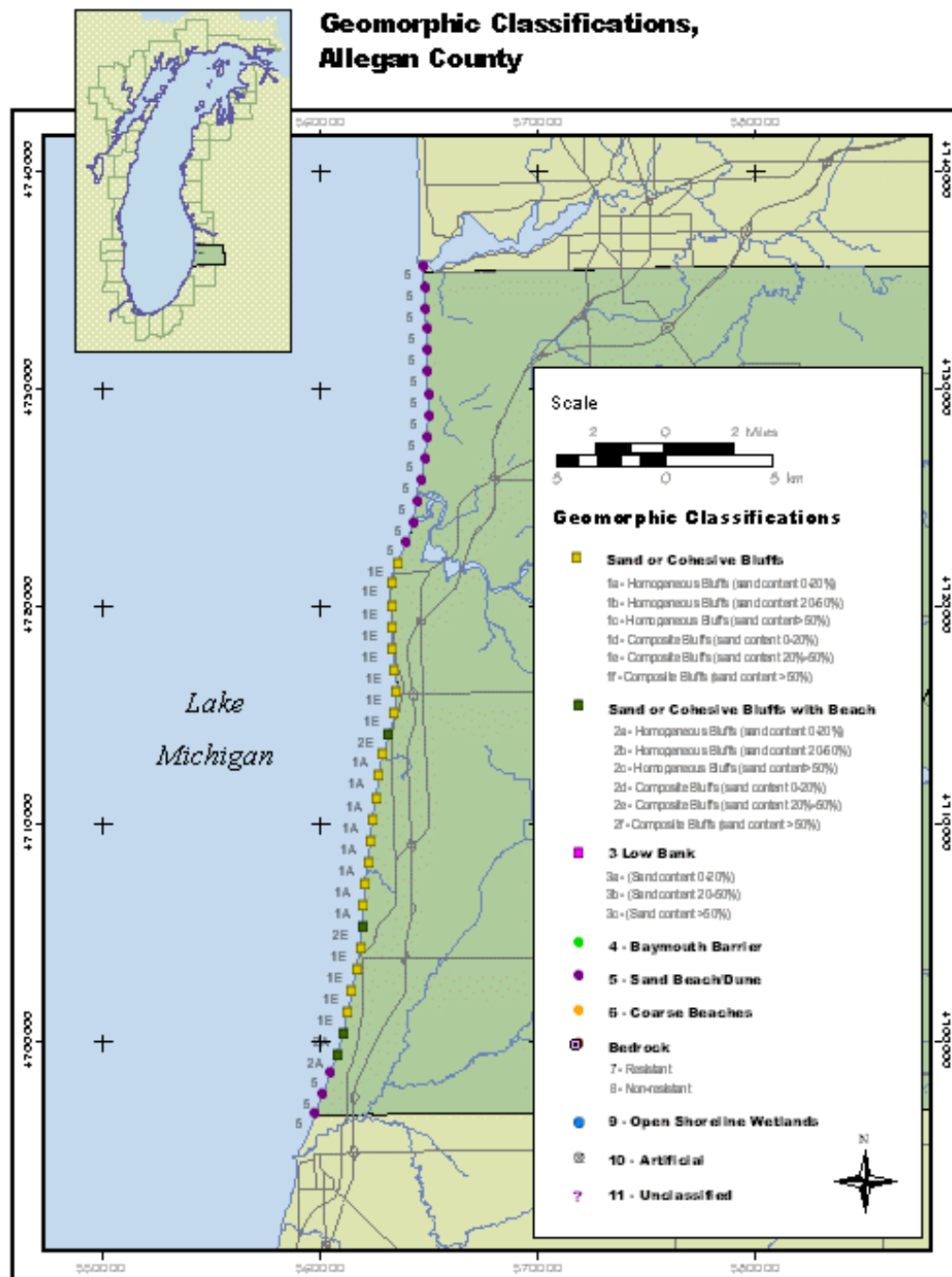
The geomorphic tier has three primary functions: to define the type of shore erosion processes (i.e. cohesive bluffs vs. sandy dunes); quantify the percent of littoral sediment in the eroded shore materials (i.e. percent sand and gravel vs. clay); and identify areas susceptible to flooding damage. An example of the geomorphic classification for Allegan County is presented in Figure 3.19. The northern third of the county is classified as sand beach / dune, while the southern two-thirds of the Allegan are sandy or cohesive bluffs.

### **3.2.2     *Nearshore Tier***

The nearshore tier of the classification provides data on the surficial substrate of the lake bottom (i.e. sandy, cohesive or bedrock) and an estimate for the volume of sand cover above the underlying substratum. The nearshore sub-aqueous tier for Allegan County is presented in Figure 3.20. Again, the northern third of the County features a sandy lake bed, while the remaining reaches feature either a glacial till substrate or a cobble boulder lag deposit.

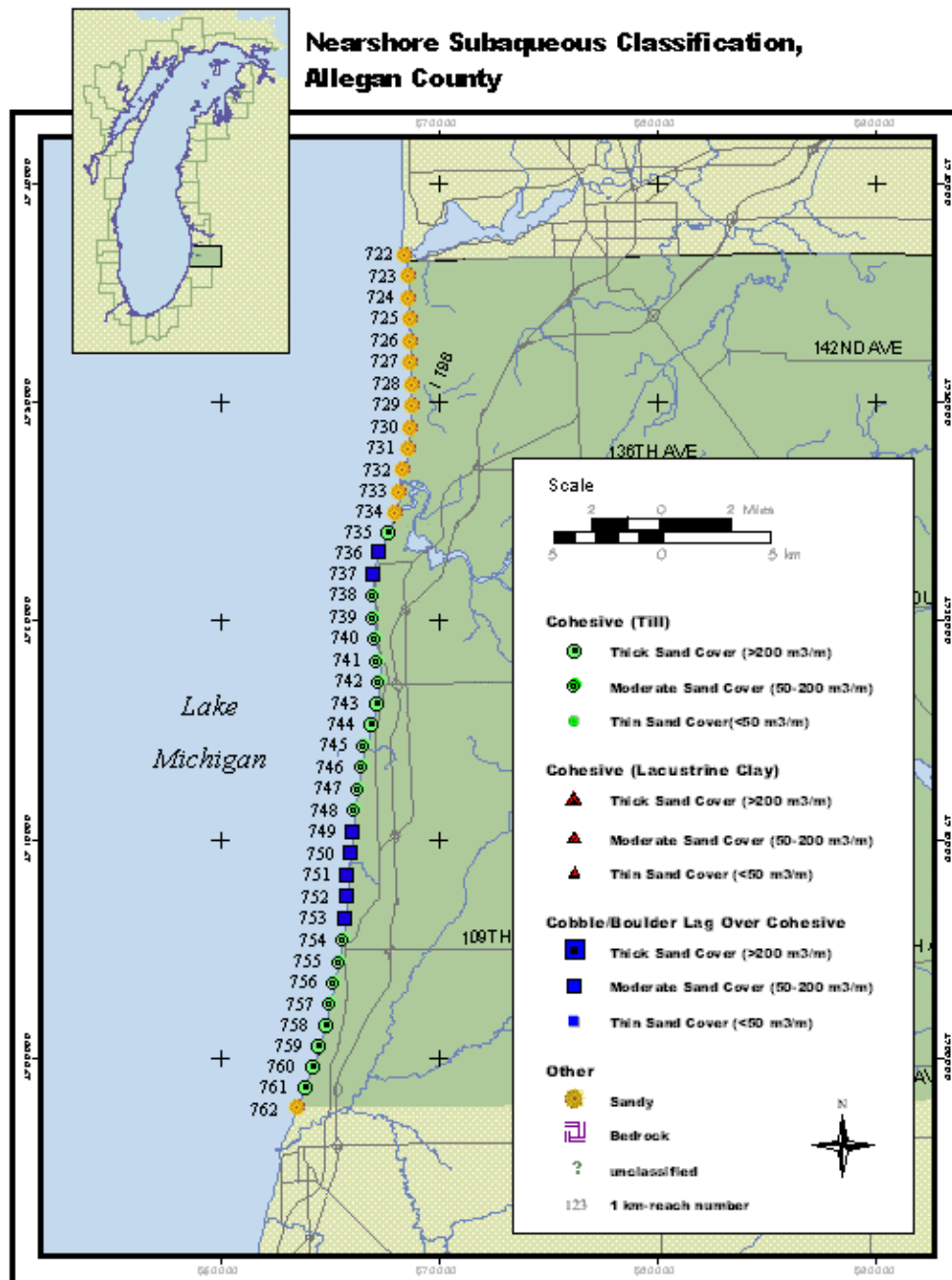
### **3.2.3     *Shore Protection Tier***

When the shoreline classification was updated for Lake Michigan in FY98, the amount, type, and design life of shoreline protection was noted for each 1 km reach. The shoreline protection tier was subsequently re-classified based on new 100 m sub-reaches in FY99



**Figure 3.19 1 km Geomorphic Classification, Allegan County**

(USACE, 2000). A sample of the results are provided in Table 3.4 for Reach 0683 in Ottawa County. At each 100 m interval, the length and type of shoreline protection was noted based on the 1999 aerial photographs. The 100 m data for the shore protection tier was incorporated in the modeling of future shoreline position, which is described in Section 5.0 of the report.



**Figure 3.20 1 km Nearshore Subaqueous Classification, Allegan County**

**Table 3.4**  
**Detailed Shoreline Protection Mapping and Classification (Ottawa County)**

Reach	Sub Reach (1/10th km)	Lat. / Long.	1989		1999		CHANGE (m)
			Type	Length	Type	Length	
683	683-1	43.11103/-86.26812	7	100	7	100	0
	683-2	43.11022/-86.26750	7	100	7	100	0
	683-3	43.10935/-86.26713	7	100	7	100	0
	683-4	43.10860/-86.26669	7	100	7	100	0
	683-5	43.10774/-86.26626	7	100	7	100	0
	683-6	43.10680/-86.26608	1B2	0	1B2	36	36
			7	100	7	64	-36
	683-7	43.10606/-86.26545	7	100	7	100	0
	683-8	43.10519/-86.26527	7	100	7	100	0
	683-9	43.10439/-86.26501	2A2	100	2A2	100	0
	683-10	43.10352/-86.26458	2A2	100	2A2	100	0

## **4.0 EROSION PROCESSES AND FEPS MODELING**

The three primary open coast shore types for the Great Lakes were introduced in Section 3.2 of the report. Section 4.0 will provide a discussion of the erosion processes for these three unique shore types, with particular attention to the influence of lake levels. The FEPS erosion prediction methodology is presented in the context of the shoreline classification and the three primary shore types.

### **4.1 Erosion Processes**

The physical processes that control the long term evolution of sandy, cohesive and bedrock shore types on the Great Lakes are fundamentally different (Philpott, 1984; Bishop et al., 1992). This recognition was one of the primary reasons for developing the 1 km shoreline classification on Lake Michigan, since the three main shoreline types will require different modeling techniques to predict future shoreline position under the LMPDS lake level scenarios.

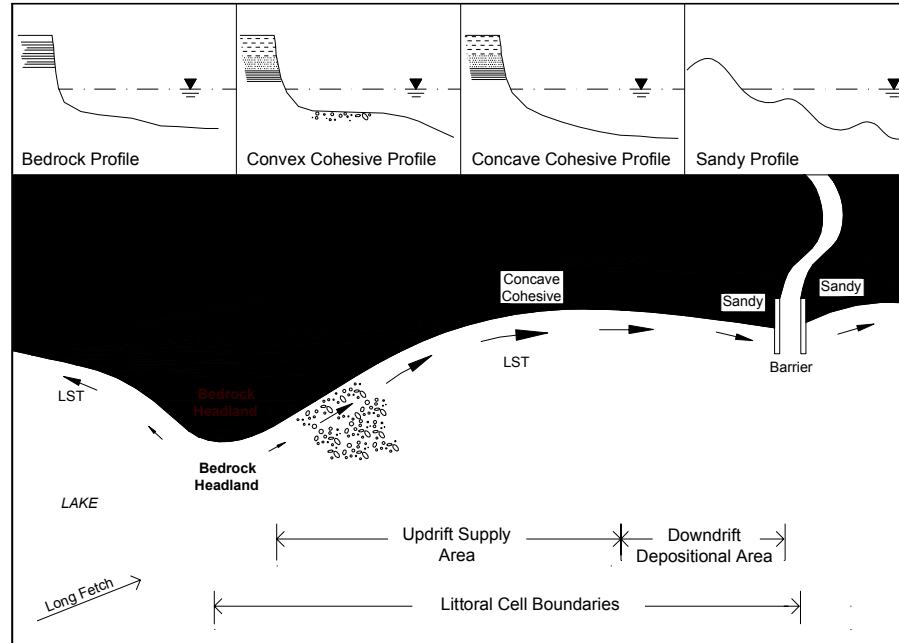
The role of erosion, sedimentation, and longshore sediment transport in the long term evolution of the three shore types will be presented within the context of a hypothetical littoral cell, presented in Figure 4.1. The erosion and sedimentation processes for these three main shore types are discussed briefly to provide background for the modeling techniques utilized in the FEPS, which are discussed in Section 4.2.

A littoral cell is a concept utilized to identify shoreline compartments or sediment boundaries based on the supply, transport and re-distribution of sand and gravel sized material along the shore (MNR, 1988). Within a littoral cell, there is generally a net direction of longshore sediment transport (LST) due to the incident wave climate and there is no (or only minimal) leakages of sediment at the cell boundaries. In the case of the hypothetical littoral cell in Panel A of Figure 4.1, a bedrock headland defines the updrift boundary, while the harbor jetties create a littoral barrier and represents the limits of the downdrift depositional area. The littoral cell model in Figure 4.1 is discussed further in the following sections on bedrock, cohesive and sandy shorelines.

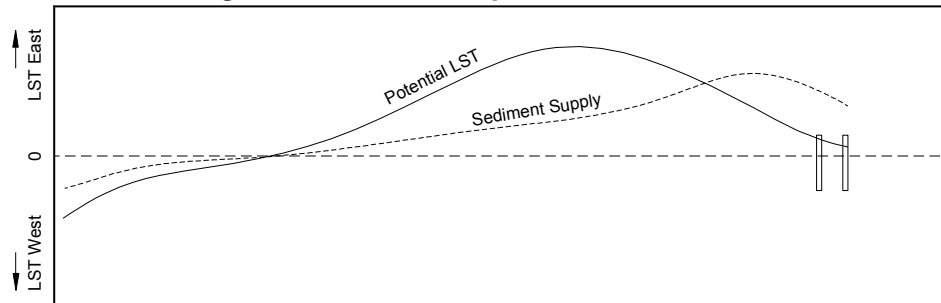
#### **4.1.1 Bedrock Shorelines**

As Table 3.3 illustrated, approximately 15% of the Lake Michigan shoreline has been classified as bedrock in the geomorphic tier. Figure 4.2a presents an alongshore view of a typical bedrock shoreline on the Great Lakes. The nearshore lake bed and bluff toe have developed in weak shale and limestone. The shale is capped with glacial till, clay and sand. The eroding bluff face is void of vegetation, with the exception of fallen tree's from the tablelands.

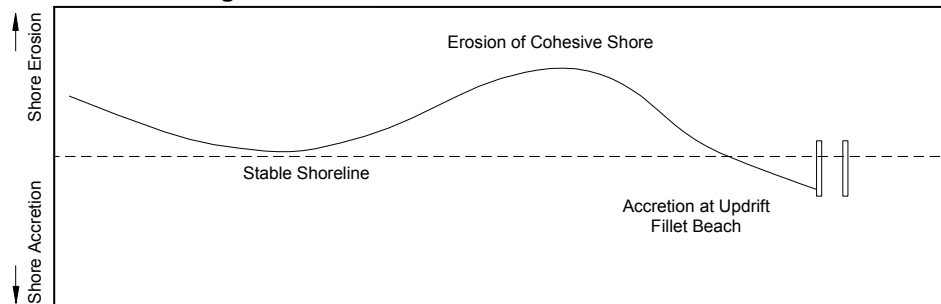
**PANEL A: Conceptual Littoral Cell**



**PANEL B: Longshore Sediment Transport**



**PANEL C: Long Term Shoreline Trend**

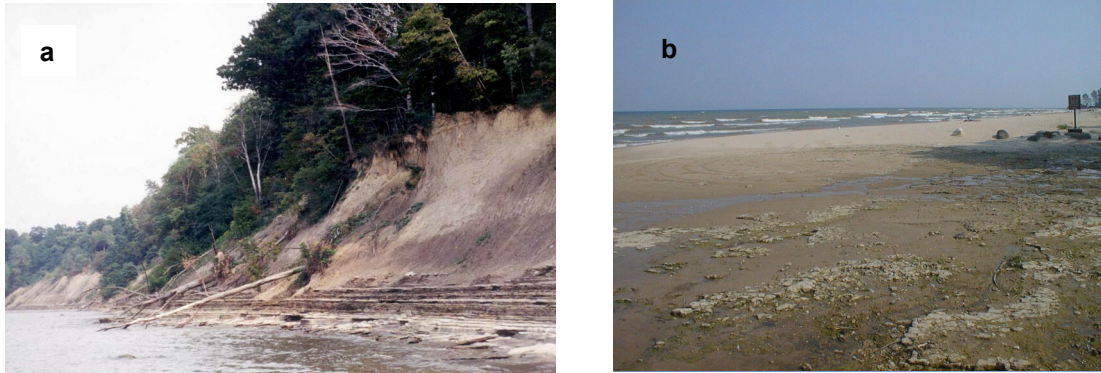


Adopted from Davidson-Arnott, 1990

**Figure 4.1 Future Top of Bank Algorithm for Cohesive Shores**

Within the five prototype counties investigated in 1999 and 2000, none of the 1 km reaches featured a geomorphic classification of bedrock (i.e. exposed bedrock forming the eroding shoreline). However, the northern third of Ozaukee County and the southern

third of Sheboygan County in Wisconsin were classified as bedrock for the nearshore tier (i.e. lake bed surficial characteristics). An example of exposed bedrock, observed on the beach at Reach 1210 in July 2000, is presented in Figure 4.2b.



**Figure 4.2 Bedrock Shoreline (a) and Exposed on Beach (b)**

The mechanical forces of wave action in the nearshore and wave attack at the base of rocky bluffs are the primary mechanism leading to shore platform development and bluff erosion for bedrock coasts (Sunamura, 1992; Trenhaile and Mercan, 1984). The key physical processes associated with erosion of bedrock shores are: air compression in joints and other crevices; the generation of high shock pressures by breaking waves; abrasion by rock fragments, sand and gravel; frost action; expansion due to freezing; and temperature-dependant wetting and drying (Hudec, 1973; Trenhaile, 2000; Sunamura, 1992).

Although bedrock shores are erodible under direct wave attack and other physical/chemical processes, they are generally more erosion resistant than cohesive and sandy shorelines. Therefore, as seen in Panel A of the littoral cell model in Figure 4.1, the bedrock outcrop results in the development of a prominent headland feature that forms the updrift littoral cell boundary. The direction and magnitude of the net LST rates are presented by the arrows in Panel A to highlight the influence of the headland on transport directions (i.e. creation of a divergent node).

#### **4.1.2 Cohesive Shorelines**

A typical eroding cohesive bluff is presented in Figure 4.3. Coastal bluffs represent approximately 16% of the 1 km shoreline reaches on Lake Michigan (Table 3.3). An unknown percentage of the low bank classification, which covers an additional 15% of the lake, also represents cohesive shorelines. Therefore, this shore type is likely representative of over 20% of the Lake Michigan shoreline. For reference, Davidson-

Arnott (1990) has estimated that approximately 40% of the lower Great Lakes (Ontario, Erie, and Huron) have evolved through relatively weak Quaternary glacial, glacio-fluvial and glacio-lacustrine sediments that are representative of the cohesive shore type.

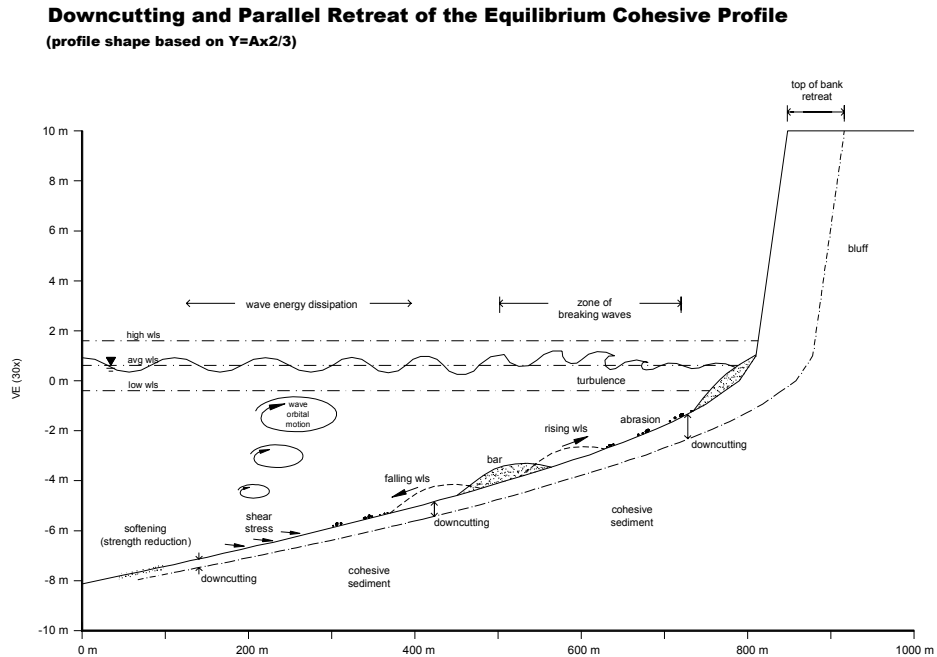


**Figure 4.3 Eroding Cohesive Bluff**

A shore is defined as cohesive when erosion of the consolidated shore materials, such as glacial till and glacio-lacustrine deposits occupies the dominant role in changes to the morphology of the shoreline (Nairn and Holmes, 1988). In other words, underneath any cohesionless deposits (i.e. sand and gravel), there is an erodible cohesive substratum, and the erosion of this material is the primary driving force that determines how and at what rate the shore evolves. Once the consolidated material is eroded, it can not reconstitute itself in the energetic coastal environment, and therefore, cohesive shoreline erosion is irreversible.

The important role of lake bed downcutting in the long term evolution of cohesive shorelines on the Great Lakes has been documented by field measurements (Davidson-Arnott, 1986), investigations of historic profile evolution (Philpott, 1983; Nairn, 1992), laboratory investigations (Nairn, 1986; Bishop et al., 1992; Kamphuis, 1990), numerical modeling (Nairn et al., 1986), and a 3D lake bed comparison (Nairn et al., 1997). The above noted studies, along with Kamphuis (1987), concluded that the amount of lake bed downcutting increases in an onshore direction. As the shore evolves in a landward direction, the profile form maintains a concave form that is well represented by the equilibrium profile concept of Dean (1977).

The equilibrium profile concept is depicted visually in Figure 4.4. As the lake bed or shore platform erodes, the profile maintains its form while migrating in a landward direction. Several of the key physical processes responsible for erosion of the cohesive profile are noted on Figure 4.4, including the generation of shear stresses at the bed due to wave orbital motion and downcutting in the nearshore profile due to turbulence generated by breaking waves. These two fundamental processes are simulated in the COSMOS model and discussed further in Section 4.2.



**Figure 4.4 Eroding Cohesive Bluff**

Since the fraction of sand and gravel in the soil matrix is generally in the range of 10 to 25% for cohesive shorelines (Davidson-Arnott and Ollerhead, 1995), volumetric losses due to bluff erosion are not balanced by an equal amount of nearshore deposition. Therefore, only intermittent deposits of sand and gravel accumulate on the beach and in nearshore sand bars for cohesive shores, while the remaining fine sediment from bluff erosion (i.e. silts and clays) are transported in an offshore and alongshore direction (Bishop, et al., 1992).

There can be exceptions to the rule of minimal sand cover in the nearshore above the cohesive substratum, especially at sites which feature relic sand deposits in the bluff, and thus a higher fraction of sand in the soil matrix. When sand volumes in the nearshore exceed the thicknesses of active sediment motion during storm events, the sand cover can protect the underlying cohesive substratum from downcutting. Nairn (1992) determined that when the volume of cohesionless nearshore sediment was in excess of  $250 \text{ m}^3/\text{m}$ , the

underlying cohesive substratum was protected from downcutting. When sand cover volumes of less than  $250 \text{ m}^3/\text{m}$  occur, the sediment cover is often intermittent and exposed cohesive lake bed is common. The shoreline classification for the nearshore tier includes an estimate of sand cover volume above the cohesive substratum to account for the influence of sand cover on the erosion process.

In Figure 4.4, the parallel retreat of the equilibrium lake bed profile is extended above the waterline and includes the cohesive bluff. Over long time periods (i.e. years to decades), lake bed downcutting is the sustaining processes that leads to bluff toe erosion and large failures. The downcutting processes allows large waves to propagate into the beach and attack the bluff toe, especially during high lake levels. Without ongoing lake bed lowering, eventually a very wide dissipative beach or shelf would develop at the base of the bluffs and the slope would stabilize. However, in the long term, this stability is rarely achieved for unprotected shorelines, since the downcutting of the nearshore lake bed continually exposes the bluff toe to wave attack.

Over shorter time frames, such as storm events or several months of sustained high lake levels, the bluff toe will erode under direct wave attack. An example of bluff toe erosion at the Miami Park site in August of 1997 during a high lake level period is presented in Figure 4.5. The physical factors that cause toe erosion and the removal of slumped debris include: abrasion due to sediment entrained by breaking waves and wave uprush;

hydraulic and pneumatic pressures; turbulence due to wave breaking; and compression, tension, and cavitation (Carter and Guy, 1988; Amin and Davidson-Arnott, 1995). Collectively, these physical processes are simulated in the COSMOS model with a bluff erodibility coefficient, which must be calibrated based on historic toe erosion rates. The calibration process is discussed in further detail in 4.2.2.



**Figure 4.5 Bluff Toe Erosion**

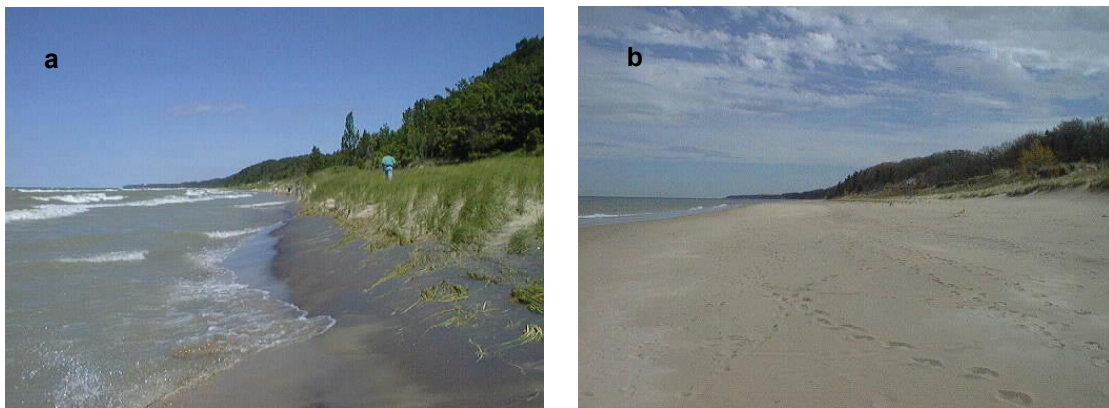
With reference to the conceptual littoral cell in Panel A of Figure 4.1, the eroding cohesive shores represent an updrift supply area for new sand and gravel. However, due to the small fraction of sand and gravel in the eroded bluffs, and thus in the nearshore zone, the potential longshore sediment transport rate exceeds the available supply. This process is illustrated graphically in Panel B of Figure 4.1 and is one of the primary reasons cohesive shorelines generally feature narrow beaches and only limited sediment

in the nearshore above the underlying cohesive substratum. It is also worth noting that information on sand cover volumes is very costly to collect over large geographic regions and consequently, measured field data is scarce.

#### **4.1.3 Sandy Shorelines**

The morphology and evolution of sandy coastlines is influenced by incident wave energy and lake levels (King, 1972), and more recently by human alterations to the coastal environment (Komar, 2000). Besides the obvious differences in the geologic properties between sandy and cohesive shorelines, a major distinction is the potential for sandy shorelines to recover from erosion events (Philpott, 1984). As discussed in Section 4.1.2, erosion of cohesive shores is irreversible.

On the Great Lakes, short term cross-shore profile response to lake level trends and severe storms are well documented (Hands, 1979; Nairn et al., 1997). During rising lake levels, a cross-shore profile response occurs as the mean water level increases, and sand from the beach and dune is transported in an offshore direction. Figure 4.6a illustrates this cross-shore adjustment for the Warren Dunes site in Berrien County during the high lake levels in August 1997. Two years later, during much lower lake levels, a wide beach has re-developed at the site (Figure 4.6b) and the foredunes were recovering from erosion during the high lake level period in 1997.



**Figure 4.6 Erosion of a sandy beach during high lake levels (a) in 1997 and accretion during low lake levels in 1999 (b)**

However, over temporal scales covering years to decades, the supply of new material, the rate of sediment movement along the shore, and natural and artificial barriers to LST are the fundamental processes that shape the morphology of a sandy coastline. In other words, gradients in longshore sediment transport are the critical factor determining

whether a sandy shoreline will be in a state of erosion or accretion. The concept is demonstrated in Figure 3.22 for the sandy shores in the littoral cell.

The updrift supply for the littoral cell in Panel A includes the eroding cohesive shores east of the bedrock headland. The dominant incident waves are from the south west and result in a net longshore sediment transport direction to the east towards the harbor jetties (arrows in Panel A). In the eastern third of the littoral cell, the sediment supply exceeds the potential longshore sediment transport rate, and a sandy shoreline develops, as demonstrated in Panel B. The harbor jetties also represents a littoral barrier, which leads to additional sediment accumulation in the form of fillet beaches and shoals offshore of the coastal structures.

Coastal structures such as the harbor jetties can represent a partial/complete littoral barrier to longshore sediment transport and thus can represent a cell boundary (or sub-cell boundary). The physical processes affecting sediment transport, and bypassing, and shoreline evolution in the vicinity of large coastal structures are complex and require detailed investigations to quantify short and long term trends.

## **4.2 Erosion Prediction Methods based on Shore Classification**

The three tiers of the shoreline classification for Lake Michigan were described in Section 3.2 of the report. A complete listing of the classification for the 82 reaches in Ottawa and Allegan Counties is provided in Table 4.1, from reach 0681 in the north, to reach 0762 in the south. The table also includes: the single value recession rate selected for the coastal modeling; the type of modeling approach (i.e. sediment budget for sandy reaches vs. COSMOS estimates for cohesive shores); the location of county boundaries and harbors. Approximately two thirds of the reaches feature a sandy classification for the geomorphic tier, with the remaining third in southern Allegan County representative of a cohesive shoreline (i.e. bluffs with glacial till lake bed).

There are 146 shoreline reaches in the three Wisconsin prototype counties, Ozaukee, Sheboygan and Manitowoc. Table 4.2 summarizes the shoreline reaches from 1318 in the north to 1172 in the south. The Wisconsin Counties exhibit a wide range of geomorphic and nearshore classification combinations, including: sandy beach / dune, low banks and bluffs for the geomorphic class; and sand, glacial till, cobble boulder lag and bedrock for the nearshore classification.

### **4.2.1 Erosion Predictions Bedrock Shorelines**

The FEPS has not yet been applied to shoreline reaches with a bedrock classification for the geomorphic tier (i.e. geology above the lake level) in either of the detailed study sites investigated in FY98 or the five prototype counties studied in FY99 and 2000. As such,

Table 4.1 COSMOS Modeling Summary for Allegan and Ottawa Counties

Reach	Geomorphic Tier	Nearshore Tier	Assumed SVRR	Shore Protection Tier From To	Type of Modeling for Predicting the 50 Year Top of Bank	Uncertainty Band for 50 Year Est.	5 m Correction Band Reach
<b>Northern Ottawa County Line</b>							
681	Dunes	Sandy			Sediment Budget		Y
682	Dunes	Sandy			Sediment Budget		Y
683	Dunes	Sandy	0.49		Sediment Budget		Y
684	Dunes	Sandy	0.61		Sediment Budget		Y
685	Dunes	Sandy	0.43		Sediment Budget		Y
686	Dunes	Sandy	0.52		Sediment Budget		Y
687	Dunes	Sandy	0.31		Sediment Budget		Y
688	Dunes	Sandy	0.09		Sediment Budget		Y
<b>Grand Haven Jetties</b>							
689	Dunes	Sandy	no data		Sediment Budget		Y
690	Dunes	Sandy	0.29		Sediment Budget		Y
691	Dunes	Glacial Till - Thick Sand	0.55		Sediment Budget		Y
692	Dunes	Glacial Till - Thick Sand	0.62		Sediment Budget		Y
693	Dunes	Glacial Till - Thick Sand	0.56		Sediment Budget		Y
694	Dunes	Glacial Till - Thick Sand	0.30		Sediment Budget		Y
695	Dunes	Glacial Till - Thick Sand	0.26		Sediment Budget		Y
696	Dunes	Glacial Till - Thick Sand	0.04		Sediment Budget		Y
697	Bluffs	Glacial Till - Thick Sand	0.39		Sediment Budget		Y
698	Bluffs	Glacial Till - Thick Sand	0.76		Sediment Budget		Y
699	Dunes	Glacial Till - Thick Sand	0.41		Sediment Budget		Y
700	Dunes	Glacial Till - Thick Sand	0.27		Sediment Budget		Y
701	Dunes	Glacial Till - Thick Sand	0.65		Sediment Budget		Y
702	Dunes	Glacial Till - Thick Sand	0.59		Sediment Budget		Y
703	Dunes	Glacial Till - Thick Sand	0.25		Sediment Budget		Y
704	Dunes	Glacial Till - Thick Sand	0.26		Sediment Budget		Y
705	Dunes	Sandy	0.52		Sediment Budget		Y
706	Dunes	Sandy	-0.30		Sediment Budget		Y
<b>Port Sheldon Jetties</b>							
707	Dunes	Sandy	-1.20		Port Sheldon Harbour		
708	Dunes	Glacial Till - Thick Sand	0.11		Sediment Budget		Y
709	Dunes	Glacial Till - Thick Sand	0.71		Sediment Budget		Y
710	Dunes	Glacial Till - Thick Sand	-0.04		Sediment Budget		Y
711	Dunes	Glacial Till - Thick Sand	0.33		Sediment Budget		Y
712	Dunes	Glacial Till - Thick Sand	0.64		Sediment Budget		Y
713	Dunes	Glacial Till - Thick Sand	0.48		Sediment Budget		Y
714	Dunes	Glacial Till - Thick Sand	0.61		Sediment Budget		Y
715	Dunes	Glacial Till - Thick Sand	0.39		Sediment Budget		Y
716	Dunes	Glacial Till - Thick Sand	0.14		Sediment Budget		Y
717	Dunes	Glacial Till - Thick Sand	0.18		Sediment Budget		Y
718	Dunes	Glacial Till - Thick Sand	0.27		Sediment Budget		Y
719	Dunes	Sandy	0.64		Sediment Budget		Y
720	Dunes	Sandy			Sediment Budget		Y
721	Dunes	Sandy	-0.49		Sediment Budget		Y
<b>Holland Arrowhead Jetties (County Line)</b>							
722	Dunes	Sandy	-0.04		Sediment Budget		Y
723	Dunes	Sandy	0.66		Sediment Budget		Y
724	Dunes	Sandy	0.48		Sediment Budget		Y
725	Dunes	Sandy	0.45		Sediment Budget		Y
726	Dunes	Sandy	0.56		Sediment Budget		Y
727	Dunes	Sandy	0.59		Sediment Budget		Y
728	Dunes	Sandy	0.27		Sediment Budget		Y
729	Dunes	Sandy	0.34		Sediment Budget		Y
730	Dunes	Sandy	0.33		Sediment Budget		Y
731	Dunes	Sandy	-0.27		Sediment Budget		Y
732	Dunes	Sandy	-1.46		Sediment Budget		Y
<b>Saugatuck Jetties</b>							
733	Dunes	Sandy	-0.68		Sediment Budget		Y
734	Dunes	Sandy	0.31		Sediment Budget		Y
735	Dunes	Glacial Till - Thick Sand	0.34		Sediment Budget		Y
736	Dunes	Cobble Boulder Lag	0.16		Sediment Budget		Y
737	Bluffs	Cobble Boulder Lag	0.43		Cohesive Modeling	Y	
738	Bluffs	Glacial Till - Mod Sand	0.75		Cohesive Modeling	Y	
739	Bluffs	Glacial Till - Mod Sand	0.55		Cohesive Modeling	Y	
740	Bluffs	Glacial Till - Mod Sand	0.30		Cohesive Modeling	Y	
741	Bluffs	Glacial Till - Mod Sand	0.68		Cohesive Modeling	Y	
742	Bluffs	Glacial Till - Mod Sand	0.60		Cohesive Modeling	Y	
743	Bluffs	Glacial Till - Thick Sand	0.54		Cohesive Modeling	Y	
744	Bluffs	Glacial Till - Thick Sand	0.33		Cohesive Modeling	Y	
745	Bluffs	Glacial Till - Mod Sand	0.37		Cohesive Modeling	Y	
746	Bluffs	Glacial Till - Mod Sand	0.24		Cohesive Modeling	Y	
747	Bluffs	Glacial Till - Mod Sand	0.47		Cohesive Modeling	Y	
748	Bluffs	Glacial Till - Mod Sand	0.58		Cohesive Modeling	Y	
749	Bluffs	Cobble Boulder Lag	0.82		Cohesive Modeling	Y	
750	Bluffs	Cobble Boulder Lag	0.37		Cohesive Modeling	Y	
751	Bluffs	Cobble Boulder Lag	0.42		Cohesive Modeling	Y	
752	Bluffs	Cobble Boulder Lag	0.55		Cohesive Modeling	Y	
753	Bluffs	Cobble Boulder Lag	0.54		Cohesive Modeling	Y	
754	Bluffs	Glacial Till - Mod Sand	0.88		Cohesive Modeling	Y	
755	Bluffs	Glacial Till - Mod Sand	0.90		Cohesive Modeling	Y	
756	Bluffs	Glacial Till - Mod Sand	0.71		Cohesive Modeling	Y	
757	Bluffs	Glacial Till - Mod Sand	0.73		Cohesive Modeling	Y	
758	Bluffs	Glacial Till - Thick Sand	0.50		Cohesive Modeling	Y	
759	Bluffs	Glacial Till - Thick Sand	0.41		Cohesive Modeling	Y	
760	Dunes	Glacial Till - Thick Sand	0.39		Cohesive Modeling	Y	
761	Dunes	Glacial Till - Thick Sand	0.30		Cohesive Modeling	Y	
762	Dunes	Sandy	0.24		Cohesive Modeling	Y	
<b>Southern Allegan County Line</b>							

**Table 4.2 COSMOS Modeling Summary**  
**Ozaukee, Sheboygan and Manitowoc Counties**

Reach	Geomorphic Tier	Nearshore Tier	Assumed SVRR	Shore Protection From	To	Type of Modeling for Predicting the 50 Year Top of Bank	Uncertainty Band for 50 Year Est.	5 m Correction Band Reach
<b>Northern Manitowoc County Line</b>								
1318	Bluffs	Cobble Lag	0.54			Cohesive Modeling	Y	
1317	Bluffs	Cobble Lag	0.66			Cohesive Modeling	Y	
1316	Bluffs	Cobble Lag	0.69			Cohesive Modeling	Y	
1315	Bluffs	Cobble Lag	0.97			Cohesive Modeling	Y	
1314	Bluffs	Cobble Lag	0.62			Cohesive Modeling	Y	
1313	Bluffs	Cobble Lag	0.38	1313-1	1313-7	Cohesive Modeling	Y	
1312	Low Bank	Glacial Till - Mod Sand	0.28	1312-7	1312-10	Cohesive Modeling	Y	
1311	Low Bank	Glacial Till - Mod Sand	0.39			Cohesive Modeling	Y	
1310	Low Bank	Glacial Till - Mod Sand	0.32			Cohesive Modeling	Y	
1309	Dunes	Sand	0.63			Sediment Budget		Y
1308	Dunes	Sand	0.70	1308-1	1308-3	Sediment Budget		Y
1307	Dunes	Sand	0.58	1307-5	1307-10	Sediment Budget		Y
1306	Dunes	Sand	0.00	1306-6	1306-8	Sediment Budget		Y
1305	Dunes	Sand	0.00			Sediment Budget		Y
1304	Dunes	Sand	0.00			Sediment Budget		Y
1303	Dunes	Sand	0.30			Sediment Budget		Y
1302	Dunes	Sand	0.00			Sediment Budget		Y
1301	Dunes	Sand	0.00			Sediment Budget		Y
1300	Dunes	Sand	0.00			Sediment Budget		Y
1299	Dunes	Sand	0.00			Sediment Budget		Y
1298	Dunes	Sand	0.00			Sediment Budget		Y
1297	Dunes	Sand	0.00			Sediment Budget		Y
1296	Low Bank	Glacial Till - Mod Sand	0.00	zero recession rate		Coastal Structures / Stable Shoreline		
1295	Two Rivers	Harbor	0.00	stable fillet beach		Coastal Structures / Stable Shoreline		
1294	Low Bank	Glacial Till - Mod Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1293	Low Bank	Glacial Till - Mod Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1292	Low Bank	Glacial Till - Mod Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1291	Low Bank	Glacial Till - Mod Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1290	Low Bank	Glacial Till - Mod Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1289	Low Bank	Glacial Till - Mod Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1288	Low Bank	Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1287	Low Bank	Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1286	Manitowoc	Harbor	0.00	full	full	Coastal Structures / Stable Shoreline		
1285	Manitowoc	Harbor	0.00	full	full	Coastal Structures / Stable Shoreline		
1284	Manitowoc	Harbor	0.00	full	full	Coastal Structures / Stable Shoreline		
1283	Bluffs	Glacial Till - Thick Sand	0.61	1283-4	1283-5	Cohesive Modeling	Y	
1282	Bluffs	Glacial Till - Thick Sand	0.38			Cohesive Modeling	Y	
1281	Bluffs	Cobble Boulder Lag	0.32			Cohesive Modeling	Y	
1280	Bluffs	Cobble Boulder Lag	0.24			Cohesive Modeling	Y	
1279	Bluffs	Cobble Boulder Lag	0.24			Cohesive Modeling	Y	
1278	Bluffs	Cobble Boulder Lag	0.27			Cohesive Modeling	Y	
1277	Bluffs	Cobble Boulder Lag	0.41			Cohesive Modeling	Y	
1276	Bluffs	Cobble Boulder Lag	0.76			Cohesive Modeling	Y	
1275	Bluffs	Cobble Boulder Lag	0.41			Cohesive Modeling	Y	
1274	Bluffs	Cobble Boulder Lag	0.47			Cohesive Modeling	Y	
1273	Bluffs	Cobble Boulder Lag	0.85			Cohesive Modeling	Y	
1272	Bluffs	Cobble Boulder Lag	0.37			Cohesive Modeling	Y	
1271	Bluffs	Cobble Boulder Lag	0.13			Cohesive Modeling	Y	
1270	Bluffs	Cobble Boulder Lag	0.09			50°SVRR (no modeling)	Y	
1269	Bluffs	Cobble Boulder Lag	0.28			Cohesive Modeling	Y	
1268	Bluffs	Cobble Boulder Lag	0.12			Cohesive Modeling	Y	
1267	Bluffs	Cobble Boulder Lag	0.25			Cohesive Modeling	Y	
1266	Bluffs	Cobble Boulder Lag	0.17			Cohesive Modeling	Y	
1265	Bluffs	Cobble Boulder Lag	0.12			Cohesive Modeling	Y	
1264	Bluffs	Cobble Boulder Lag	0.78			Cohesive Modeling	Y	
1263	Bluffs	Cobble Boulder Lag	0.48			Cohesive Modeling	Y	
1262	Bluffs	Cobble Boulder Lag	0.20			Cohesive Modeling	Y	
<b>Manitowoc - Sheboygan County Line</b>								
1261	Bluffs	Cobble Boulder Lag	0.30			Cohesive Modeling	Y	
1260	Bluffs	Cobble Boulder Lag	0.48			Cohesive Modeling	Y	
1259	Bluffs	Cobble Boulder Lag	0.27			Cohesive Modeling	Y	
1258	Bluffs	Cobble Boulder Lag	0.33			Cohesive Modeling	Y	
1257	Bluffs	Cobble Boulder Lag	0.34			Cohesive Modeling	Y	
1256	Bluffs	Cobble Boulder Lag	0.30			Cohesive Modeling	Y	
1255	Bluffs	Cobble Boulder Lag	0.28			Cohesive Modeling	Y	
1254	Bluffs	Cobble Boulder Lag	0.30			Cohesive Modeling	Y	
1253	Bluffs	Cobble Boulder Lag	0.31			Cohesive Modeling	Y	
1252	Bluffs	Cobble Boulder Lag	0.33			Cohesive Modeling	Y	
1251	Bluffs	Cobble Boulder Lag	0.30			Cohesive Modeling	Y	
1250	Bluffs	Cobble Boulder Lag	0.29			Cohesive Modeling	Y	
1249	Bluffs	Cobble Boulder Lag	0.22			Cohesive Modeling	Y	

1248	Bluffs	Cobble Boulder Lag	0.00	full	full	Coastal Structures / Stable Shoreline		
1247	Bluffs	Bedrock	0.00	full	full	Coastal Structures / Stable Shoreline		
1246	Bluffs	Bedrock	0.00	full	full	Coastal Structures / Stable Shoreline		
1245	Bluffs	Stable Filled Beach	0.00	full	full	Coastal Structures / Stable Shoreline		
1244	Sheboygan	Harbor	0.00	full	full	Coastal Structures / Stable Shoreline		
1243	Sheboygan	Harbor	0.00	full	full	Coastal Structures / Stable Shoreline		
1242	Sheboygan	Harbor	0.00	full	full	Coastal Structures / Stable Shoreline		
1241	Sheboygan	Harbor	0.00	full	full	Coastal Structures / Stable Shoreline		
1240	Bluffs	Glacial Till	0.21	1240-4	1240-10	Cohesive Modeling	Y	
1239	Bluffs	Glacial Till	0.24	1239-1 to 2	1239-8	Cohesive Modeling	Y	
1238	Bluffs	Glacial Till	0.30	full	full	Coastal Structures / Stable Shoreline		
1237	Bluffs	Glacial Till	0.61	full	full	Coastal Structures / Stable Shoreline		
1236	Bluffs	Glacial Till	0.31	full	full	Coastal Structures / Stable Shoreline		
1235	Bluffs	Glacial Till	0.33			Cohesive Modeling	Y	
1234	Low bank	Sand	0.00			Sediment Budget		Y
1233	Low bank	Sand	0.00			Sediment Budget		Y
1232	Low bank	Sand	0.00			Sediment Budget		Y
1231	Low bank	Sand	0.00			Sediment Budget		Y
1230	Low bank	Sand	0.00			Sediment Budget		Y
1229	Low bank	Sand	0.00			Sediment Budget		Y
1228	Low bank	Sand	0.00			Sediment Budget		Y
1227	Low bank	Sand	0.00			Sediment Budget		Y
1226	Low bank	Sand	0.00			Sediment Budget		Y
1225	Low bank	Sand	0.00	full	full	Coastal Structures / Stable Shoreline		
1224	Low bank	Sand	0.00			Sediment Budget		Y
1223	Low bank	Bedrock	0.00			Sediment Budget		Y
1222	Low bank	Bedrock	0.00			Sediment Budget		Y
1221	Low bank	Bedrock	0.00			Sediment Budget		Y
1220	Low bank	Bedrock	0.00			Sediment Budget		Y
1219	Low bank	Bedrock	0.00			Sediment Budget		Y
1218	Low bank	Bedrock	0.00			Sediment Budget		Y
1217	Low bank	Bedrock	0.00			Sediment Budget		Y
<b>Sheboygan - Ozaukee County Line</b>								
1216	Low bank	Bedrock	0.00			Sediment Budget		Y
1215	Low bank	Bedrock	0.00			Sediment Budget		Y
1214	Low bank	Bedrock	0.00			Sediment Budget		Y
1213	Low bank	Bedrock	0.00			Sediment Budget		Y
1212	Low bank	Bedrock	0.00			Sediment Budget		Y
1211	Low bank	Bedrock	0.00			Sediment Budget		Y
1210	Low bank	Bedrock	0.00			Sediment Budget		Y
1209	Low bank	Bedrock	0.00			Sediment Budget		Y
1208	Low bank	Bedrock	0.00			Sediment Budget		Y
1207	Low bank	Bedrock	0.00			Sediment Budget		Y
1206	Low bank	Bedrock	0.00			Sediment Budget		Y
1205	Low bank	Bedrock	0.00			Sediment Budget		Y
1204	Low bank	Bedrock	0.00			Sediment Budget		Y
1203	Low bank	Bedrock	0.00			Sediment Budget		Y
1202	Composite bluffs	Glacial Till	0.29			Cohesive Modeling	Y	
1201	Composite bluffs	Glacial Till	0.24			Cohesive Modeling	Y	
1200	Composite bluffs	Glacial Till	0.27			Cohesive Modeling	Y	
1199	Composite bluffs	Glacial Till	0.05			50°SVRR (no modeling)	Y	
1198	Composite bluffs	Glacial Till	0.09			50°SVRR (no modeling)	Y	
1197	Port Washington	Harbor		full	full	Coastal Structures / Stable Shoreline		
1196	Port Washington	Harbor		full	full	Coastal Structures / Stable Shoreline		
1195	Port Washington	Harbor		full	full	Coastal Structures / Stable Shoreline		
1194	Port Washington	Harbor		full	full	Coastal Structures / Stable Shoreline		
1193	Composite bluffs	Glacial Till	0.18			Cohesive Modeling	Y	
1192	Composite bluffs	Glacial Till	0.12			Cohesive Modeling	Y	
1191	Composite bluffs	Glacial Till	0.14			Cohesive Modeling	Y	
1190	Composite bluffs	Glacial Till	0.09			50°SVRR (no modeling)	Y	
1189	Composite bluffs	Glacial Till	0.39			Cohesive Modeling	Y	
1188	Composite bluffs	Glacial Till	0.24			Cohesive Modeling	Y	
1187	Composite bluffs	Glacial Till	0.12			Cohesive Modeling	Y	
1186	Composite bluffs	Glacial Till	0.18			Cohesive Modeling	Y	
1185	Composite bluffs	Glacial Till	0.49			Cohesive Modeling	Y	
1184	Composite bluffs	Glacial Till	0.21			Cohesive Modeling	Y	
1183	Composite bluffs	Glacial Till	0.27			Cohesive Modeling	Y	
1182	Composite bluffs	Glacial Till	0.23			Cohesive Modeling	Y	
1181	Composite bluffs	Glacial Till	0.51			Cohesive Modeling	Y	
1180	Composite bluffs	Glacial Till	0.05			50°SVRR (no modeling)	Y	
1179	Composite bluffs	Glacial Till	0.21			Cohesive Modeling	Y	
1178	Composite bluffs	Glacial Till	0.09			50°SVRR (no modeling)	Y	
1177	Composite bluffs	Glacial Till	0.14			Cohesive Modeling	Y	
1176	Composite bluffs	Glacial Till	0.18			Cohesive Modeling	Y	
1175	Composite bluffs	Glacial Till	0.47			Cohesive Modeling	Y	
1174	Composite bluffs	Glacial Till	0.56			Cohesive Modeling	Y	
1173	Composite bluffs	Glacial Till	0.37			Cohesive Modeling	Y	
1172	Composite bluffs	Glacial Till	0.50			Cohesive Modeling	Y	
<b>Southern Ozaukee County Line</b>								

the erosion processes and rates of bluff retreat for a bedrock site have not been documented. Consequently, a modeling approach for reaches with a bedrock classification in the geomorphic tier has not been developed.

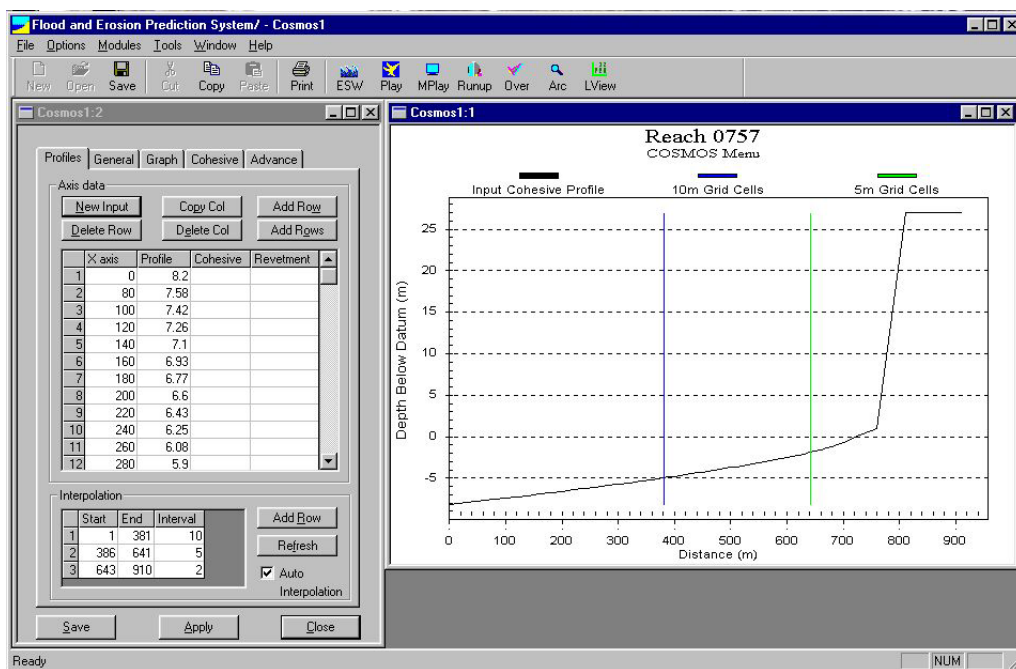
Within the three Wisconsin Prototype Counties, 21 of the 1 km shoreline reaches were classified as bedrock lake bed. Since there was no 1999 SHOALS data to compare to the 1913 NOAA survey, it was not possible to document changes to the lake bed (i.e. depths and slope). Therefore, for modeling purposes the lake bed was assumed to be stable over the 50 year prediction period.

#### 4.2.2 *COSMOS Erosion Predictions for Cohesive Shores*

Erosion predictions for cohesive shores with the FEPS are completed with the COSMOS module, as outlined in Section 2.2.5.2. There are three main modeling steps for cohesive shore erosion predictions with COSMOS, as outlined in the sections below, including preparation of an input menu with the FEPS, calibration of the erodibility coefficients, and model estimates for the LMPDS lake level scenarios.

##### 4.2.2.1 *COSMOS Menu Tool in the FEPS*

The functionality of the COSMOS model has been imbedded in the FEPS and is accessed through the UI to provide a user friendly environment for creating the input menu, calibrating the model and running the future scenarios. Figure 4.7 presents the model interface developed for the FEPS UI. Profile data extracted from the GIS (discussed in



**Figure 4.7** Interface for the COSMOS Model in the FEPS

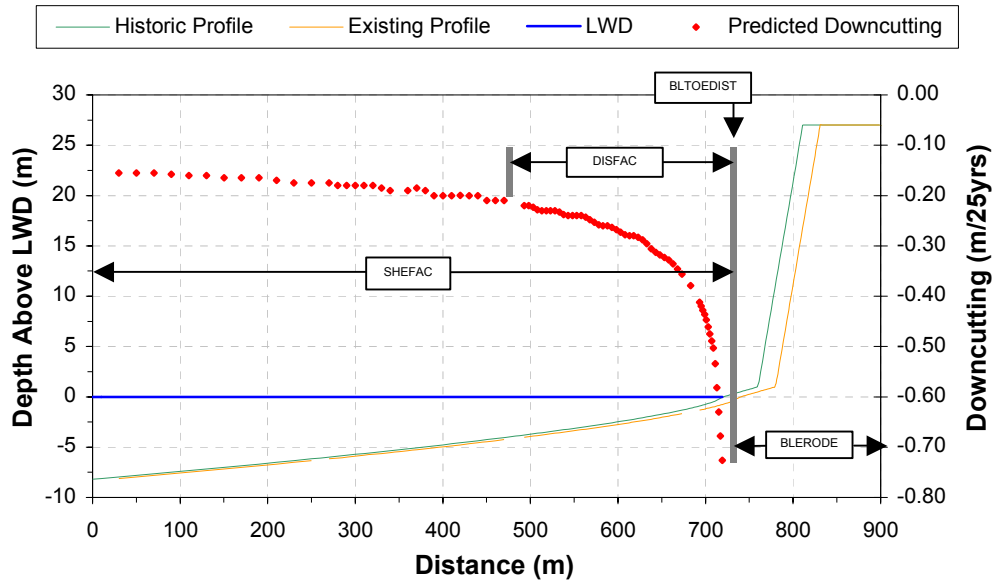
Section 2.2.3) is imported from the coastal database and automatically graphed in the chart window. The user can update and modify the profile data and immediately visualize the results.

The additional tabs in the COSMOS interface (General, Graph, Cohesive, and Advance) contain model parameters that must be specified by the user, such as sediment grain size in the General Tab and the erodibility coefficients in the Cohesive Tab. Once the menu generation is complete, the file is saved in the coastal database.

#### *4.2.2.2 Calibration of the Erosion Coefficients in COSMOS*

The erosion of cohesive shorelines on the Great Lakes was described in Section 4.1.2. Prior to predicting erosion with the COSMOS model for the three LMPDS scenarios, three empirical erodibility coefficients were calibrated based on the magnitude of historic lake bed and bluff erosion. The coefficients are described below and presented graphically in Figure 4.8:

1. **BLTOEDIST:** A horizontal distance along the X-axis of the profile that marks the limit of erosion predictions based on the SHEFAC and DISFAC coefficients. Inshore of BLTOEDIST, erosion of the cohesive profile is based on the BLERODE coefficient (generally set to a distance corresponding to the LWD);
2. **SHEFAC:** As waves propagate in an onshore direction, wave orbital motion results in the generation of shear stresses at the bed, leading to erosion of the cohesive sediment. SHEFAC relates the shear stress from unbroken waves to lake bed downcutting. As Figure 4.8 demonstrates, the SHEFAC coefficient can affect downcutting of the lake bed from deep water to the waterline;
3. **DISFAC:** An empirical factor that relates the amount of wave energy dissipation during wave breaking in the surf zone to lake bed downcutting. As the fraction of broken waves increases from 0 to 1, the DISFAC coefficient receives an increasing proportion of the wave energy for the erosion estimate. Conversely, less wave energy is transferred to the SHEFAC coefficient as the fraction of broken waves approaches 1; and
4. **BLERODE:** The amount of bluff erosion that occurs landward of BLTOEDIST is related to the magnitude of wave energy at this horizontal marker distance. The hourly wave height at the BLTOEDIST distance on the X axis is related to bluff retreat by the empirical BLERODE coefficient. BLERODE must be calibrated based on historical erosion rates. The resulting top of bank position at the completion of the simulation represents the horizontal erosion estimate.



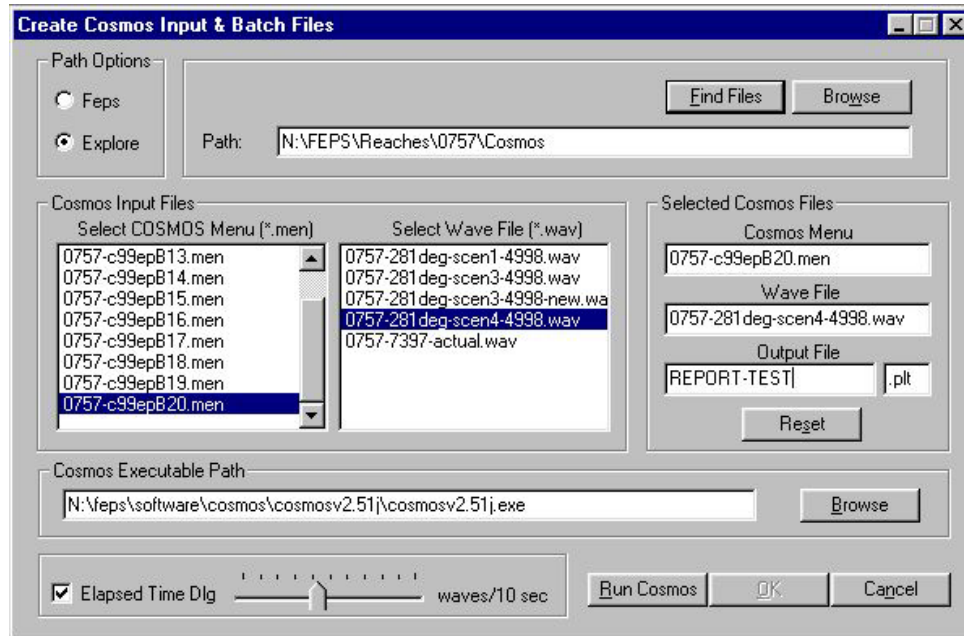
**Figure 4.8 COSMOS Erodibility Coefficients**

The three coefficients are calibrated in an iterative process in the FEPS UI. For example, the user selects appropriate values for the three coefficients and runs the COSMOS model with historic wave and lake levels that correspond to the period of measured erosion. The model predictions are compared graphically to the measured downcutting and bluff retreat, modified as required, and the model is re-run until the model prediction matches the historic profile change. Once the three erodibility coefficients are successfully calibrated, the three LMPDS lake level scenarios can be run in the COSMOS model.

#### 4.2.2.3 COSMOS Model Estimates with the FEPS

Once the COSMOS input menu is calibrated for the individual shoreline reaches, estimates of future erosion potential can be simulated for the three LMPDS scenarios. Figure 4.9 provides a screen capture of the model interface to run COSMOS from the FEPS UI. The user selects the appropriate file path in the coastal database to access input files for a particular shore reach. The model interface is populated with the available input menus (\*.men files) and wave files (\*.wav) created with the ESWave module. The user selects any combination of COSMOS menu, wave file and output file name (\*.plt) and runs the model for the 50 year simulation.

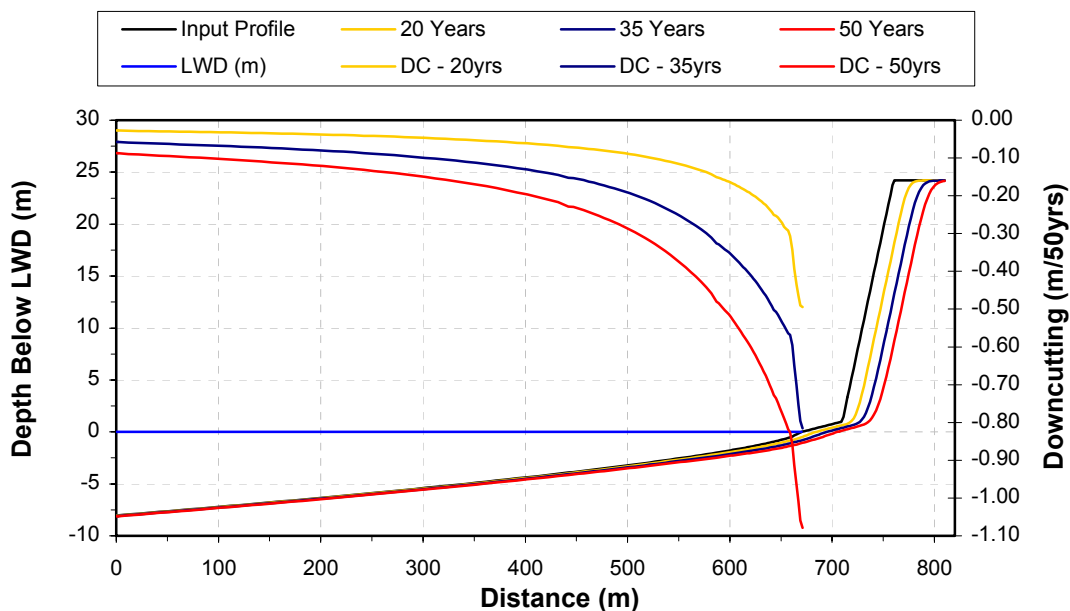
Model output is requested at two intermediate periods during the 50 year simulation, 20 and 35 years, and at the completion of the run (50 years). An example of the extreme wet scenario model results at the three time periods for Reach 0755 in Allegan County is presented in Figure 4.10. As the duration of the simulation increases, the amount of nearshore lake bed erosion increases, as the lines on the secondary Y axis indicate.



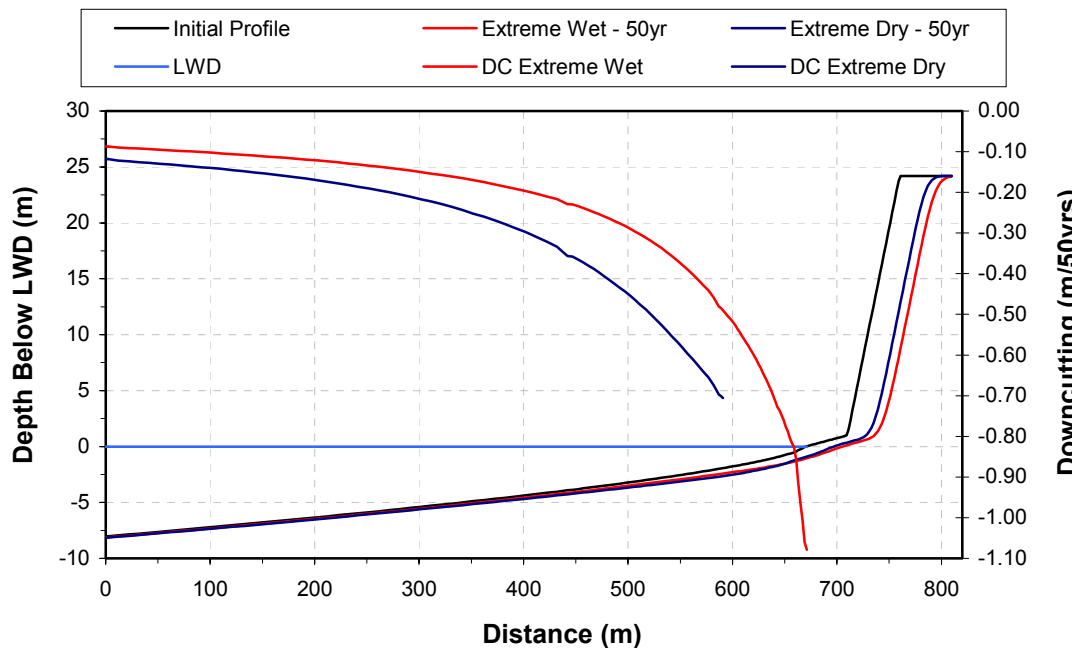
**Figure 4.9 Model Interface for COSMOS**

Corresponding to the downcutting is bluff retreat for the three time periods over the 50 year simulation.

Figure 4.11 provides the 50 year model output at Reach 0755 for the extreme wet scenario and extreme dry, which represent the two outer limits for the erosion predictions. Due to the lower lake levels in extreme dry scenario, the amount of energy dissipation



**Figure 4.10 COSMOS Erosion Estimates at Reach 0755 for Extreme Wet Scenario**



**Figure 4.11 COSMOS 50 Year Estimates for the Extreme Wet and Dry Scenarios**

and thus lake bed downcutting is significantly higher than the results for extreme wet scenario, especially in the critical nearshore zone. The trend is reversed for the amount of bluff retreat inshore of 660 m. Since the energy dissipation rate across the nearshore zone was higher for the extreme dry scenario, the amount of remaining wave energy that reaches the bluff toe (i.e. BLERODE coefficient) is significantly lower than the extreme wet model results. Therefore, the bluff erosion rate is higher for extreme wet scenario (34.2 m), versus 25.25 m for the extreme dry. It is important to reiterate that the same wave climate was used for all three 50 year LMPDS lake level scenarios and thus changes in the magnitude of nearshore downcutting and bluff retreat is attributed solely to the changes in the horizontal distribution of the wave energy dissipation (i.e. lake level effect).

### 4.2.3 Shoreline Change Estimates for Sandy Shores

Estimates of future shoreline position for the sandy reaches involves a four step process in the FEPS: 1) populate the coastal database; 2) run the sediment budget module in the FEPS to predict the historic change rates; 3) convert the net volume change per reach to a shoreline change rate; and 4) for future scenarios, alter input variable(s), such as annual beach nourishment, and re-run the sediment budget to calculate new shoreline change rates. The four steps for predicting shoreline change rates with the FEPS are discussed in further detail in the following sections.

#### 4.2.3.1 Step 1: Populate the Coastal Database

The coastal database in the FEPS is the repository for all the input variables to the sediment budget module. Prior to running the module, the user must populate the system with the necessary input variables, such as: average bluff elevation, depth of closure, historic beach nourishment records, dredging records, onshore and offshore losses of sediment, and rates of longshore sediment transport. An example of the dredging and beach nourishment history at Grand Haven from 1985 to 1987 is presented in Table 4.3. Other variables, such as the shoreline geology for the individual reaches and the percentage of sand and gravel in the bluffs is extracted from the shoreline classification.

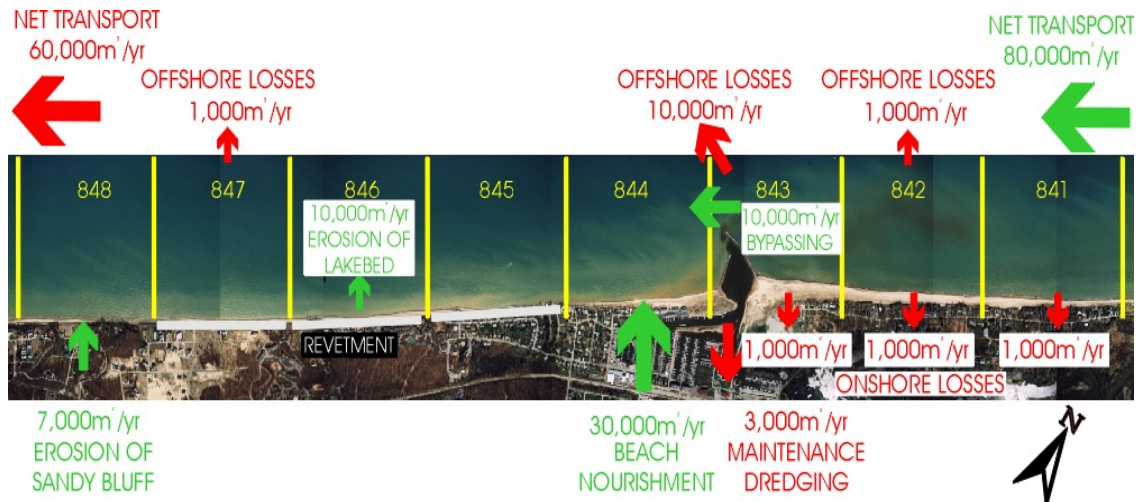
**Table 4.3**

LOCATION	DATE	DREDGING HISTORY			NOURISHMENT HISTORY			
		REACH	DREDGE m <sup>3</sup> /yr	YEARLY m <sup>3</sup> /yr	REACH	TRUCKED TO SITE (m <sup>3</sup> /yr)	FROM DREDGE m <sup>3</sup> /yr	YEARLY m <sup>3</sup> /yr
Grand Haven	2/Aug/85	689	7,646		689		7,646	
Grand Haven	2/Aug/85	689	15,154		689		15,154	
	<b>1985</b>			<b>22,799</b>				<b>22,799</b>
Grand Haven	8/Jan/86	689			689	9,718		
Grand Haven	6/Apr/86	689	12,831		689		12,831	
Grand Haven	13/Jun/86	689			689	44,599		
Grand Haven	13/Jun/86	689			689	17,839		
Grand Haven	13/Jun/86	689			689	25,485		
Grand Haven	13/Jun/86	689			689	29,945		
	<b>1986</b>			<b>12,831</b>				<b>140,417</b>
Grand Haven	8/May/87	689	9,908		689		9,908	
Grand Haven	8/May/87	689	4,880		689		4,880	
Grand Haven	8/May/87	689	2,370		689		2,370	
	<b>1987</b>			<b>17,158</b>				<b>17,158</b>

#### 4.2.3.2 Step 2: Run the Sediment Budget Module for Historic Condition

Once the coastal database has been populated for the appropriate reach boundaries, the sediment budget module is launched from the FEPS user interface. The primary input menus for the module were presented in Section 2.2.6 of the report (Figures 2.11a to c). A graphic example of the input and output variables for the reaches surrounding New Buffalo Harbor are presented in Figure 4.12.

There are two primary objectives of Step 2: a) quantify all sinks and sources for the reach boundaries of the sediment budget, and b) close the sediment budget (i.e. sources = sinks). The process is often iterative and requires the user to work interactively with the module.



**Figure 4.12 Sources and Sinks for the Sediment Budget**

#### 4.2.3.3 Step 3: Convert the Sediment Budget Results to Shoreline Change Rates

At the completion of Step 2, the Sediment Budget module generates an annual net volume change for the individual shoreline reaches within the limits of the analysis. The net volume change is then converted to a shoreline change rate. A hypothetical example is presented in Figure 4.13, along with the equation for computing a shoreline change rate (SCR):

1. Based on the results of the sediment budget, the net volume change (VOL) for the Reach is 10,000 m<sup>3</sup>/yr (erosion);
2. The shoreline length (L) is 1 km or 1,000 m;
3. The average bluff height for the 1 km (1,000 m) reach is 10 m and depth of closure is 8 m below low water datum. Combined, the two elevations provide the active depth of sediment movement (ADSM = 18 m);
4. Volume changes for the reach are calculated by the following formula:

$$VOL = L * ADSM * SCR$$

Where VOL is equal to the volume change for the reach, L is the length of the shoreline reach, ADSM is the active depth of sediment movement, and SCR is the shoreline change rate.;

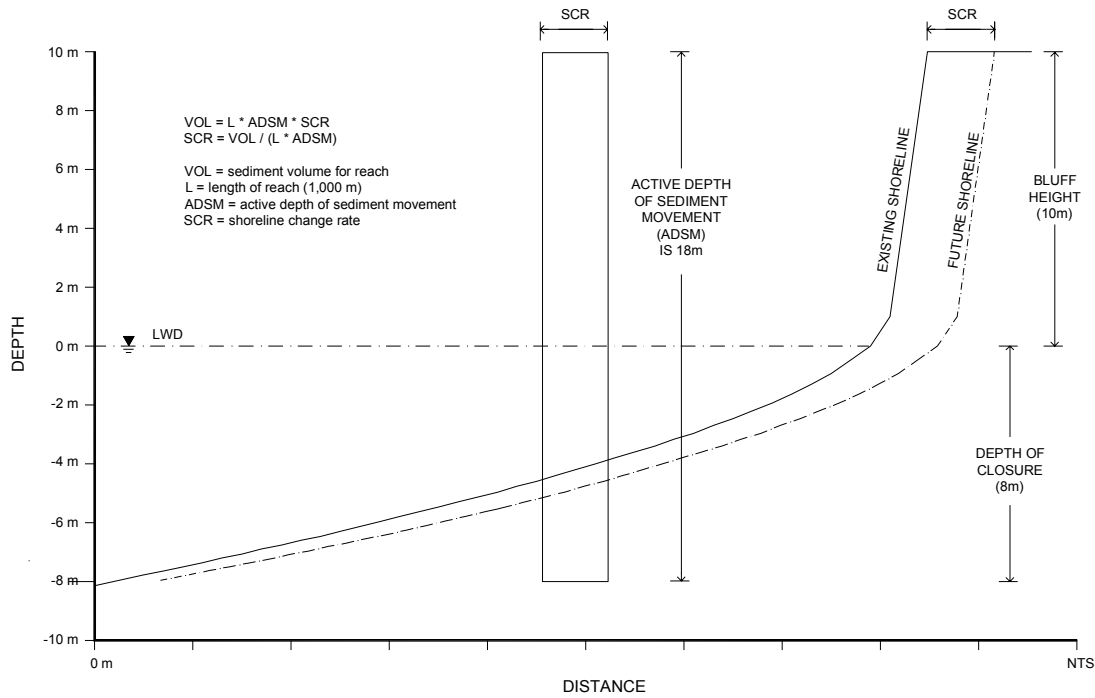
5. The SCR, which is the unknown parameter, is calculated by:

$$SCR = VOL / (L * ADSM)$$

6. For the example in Figure 4.13, the shoreline change rate based on the net volume change from the sediment budget is:

$$SCR = 10,000 / (1,000 * 18)$$

$$SCR = 0.56 \text{ m/yr.}$$



**Figure 4.13 Computing Shoreline Change Rates from Sediment Budget Volumes**

#### 4.2.3.4 Step 4: Test Future Scenarios

Once the sediment budget is closed (input and output variables are equal) and the corresponding shoreline change rates match the historic data on top of bank/dune crest retreat, future scenarios can be tested. For example, at harbors, improved sediment management practices and beach nourishment can be investigated to determine the influences on shoreline change rates. For the LMPDS scenarios, the influences of the future monthly lake level means on the sediment budget are investigated.

## 5.0 EROSION ASSESSMENTS FOR PROTOTYPE COUNTIES

The five prototype counties featured a varied and often complex combination of nearshore surficial geology and bluff stratigraphy. The 1 km shoreline classification system was used to group together reaches of similar shore conditions and define the modeling approach to be utilized in the FEPS (i.e. sandy versus cohesive shores). A total of six distinctive modeling units were identified for the five prototype counties. The physical setting of the modeling units is described, along with the shoreline classification, the presence of harbors, a discussion of available coastal data, the detailed FEPS modeling, comments on the results and recommendations.

### 5.1 Ottawa and Northern Allegan County – Sediment Budget 0681 to 0736

Ottawa and Allegan Counties are located along the south central shore of Lake Michigan. A 56 km stretch of shoreline, from Reach 0681 to 0736, was designated as sandy beach / dune for the geomorphic tier of the shoreline classification (Figure 5.1). The backshore features relic dune deposits, exceeding 30 m in height in some locations. The nearshore was classified as primarily sandy, with the exception of some reaches between Grand Haven and Holland, which were identified as glacial till with thick sand cover (i.e.  $>200 \text{ m}^3/\text{m}$ ).

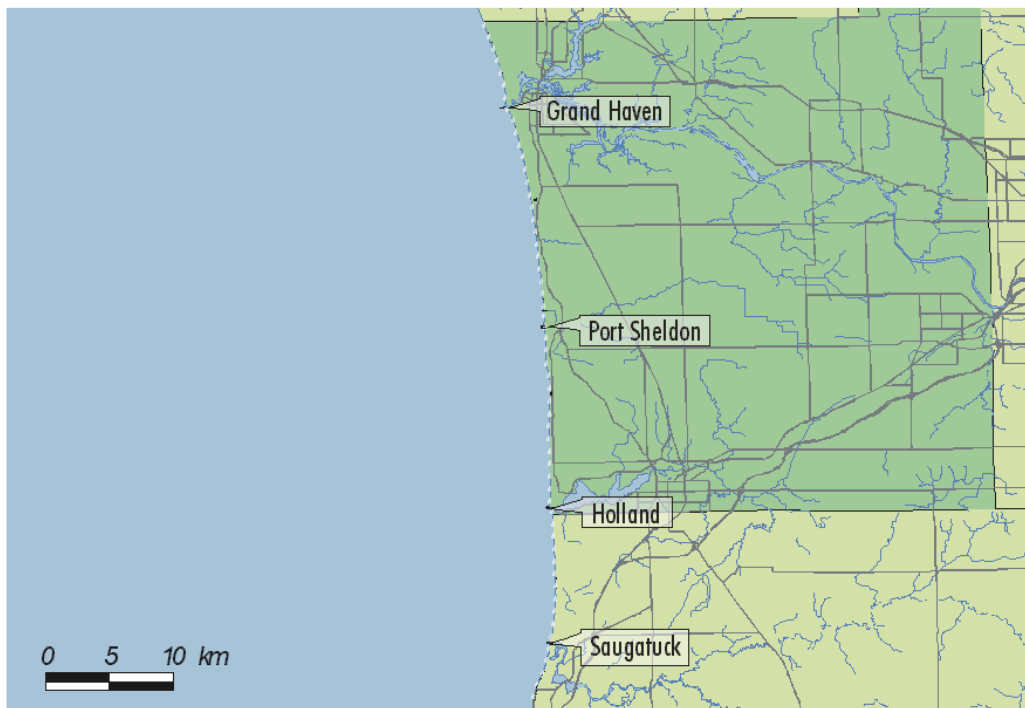


Figure 5.1 Ottawa and Northern Allegan County, Lake Michigan

The shoreline is divided into a series of sub-littoral cells by the Federal Harbor structures at Grand Haven, Holland and Saugatuck and the jetties at Port Sheldon. The influence of the three LMPDS lake level scenarios on shoreline evolution were investigated with the sediment budget module in the Flood and Erosion Prediction System. The following sections will discuss the coastal data, populating the coastal database, running the sediment budget module and the future predictions.

### **5.1.1 Coastal Data**

The SHOALS survey in the fall of 1999 provided detailed bathymetric data for Allegan County, with the exception of approximately 3 km in the vicinity of the Saugatuck jetties. Inshore of the 2 m contour, water clarity issues and wave action during the SHOALS flights limited data collection in this zone. Therefore, a data gap exists from the 2 m depth contour to the bluff toe line, at approximately 1 to 2 m above LWD. Depending on the slope of the nearshore zone, the gap in data ranged from a 100 to 200 m wide zone.

In Ottawa County, the SHOALS survey only covered approximately half of the reaches and provided no data around the Grand Haven jetties. The 1999 bluff toe and top of bank mapping provided data on the sub-aerial portion of the reaches for all of Allegan and Ottawa.

A wind wave hindcast (with Baird software), completed at WIS Station 53 offshore of Ottawa County, provided the hourly wave data for the numerical modeling. Historic lake level data at the Holland gage was utilized in the model calibration and the generation of the hourly lake level difference file. Ice data was available from the coastal database on a reach by reach basis.

### **5.1.2 Population of the Coastal Database**

The analysis completed with the FEPS to populate the coastal database is discussed, including assessment of Single Value Recession Rates (SVRR), sediment budget inputs and outputs, and numerical modeling.

#### **5.1.2.1 Single Value Recession Rates**

Single Value Recession Rates were available for two time periods in Ottawa and Allegan Counties: 1) 1938 to 1970/'73 and 2) 1938 to 1988/'89. The data is summarized in Table 5.1, records the location of the harbors and highlights SVRR for reach sw accretion in the fillet beaches. When the results for the two temporal period were reviewed, a distinctive trend of higher SVRR for the data ending in 1988/89 was observed. For example, the overall average for the 1938 to 1970/'73 SVRR from Reach 682 to 736 was

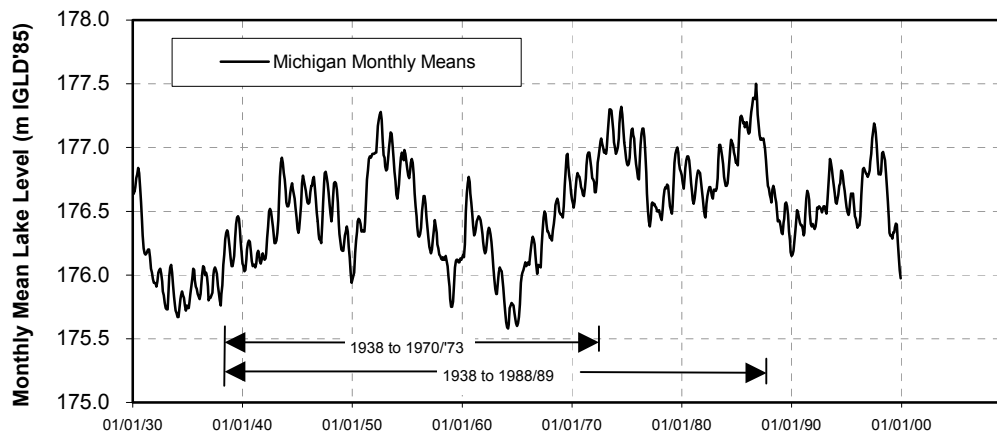
**Table 5.1**  
**SVRR for Ottawa and Allegan County Sandy Reaches**

Reach	SVRR			STATISTICS				
	1938 to 1970/73/78 (m/yr)	1938 to 1988 (m/yr)	Increase B/wn'38-'73 and '38-'88	Avg. Increase in AER (m/yr)	1 Stand. Dev. of Increase (m/yr)	% Increase per Reach		
682	0.3	0.3	0	0.15	0.19	0%		
683	0.49	0.98	0.49			100%		
684	0.61	0.56	-0.05			-8%		
685	0.43	0.59	0.16			37%		
686	0.52	0.61	0.09			17%		
687	0.31	0.51	0.2	0.17	0.21	65%		
688	0.09	0.21	0.12					
GRAND HAVEN JETTIES								
689		0	0					
690	0.29	0.24	-0.05					-17%
691	0.55	0.7	0.15			27%		
692	0.62	0.65	0.03			5%		
693	0.56	0.73	0.17			30%		
694	0.3	1.09	0.79			263%		
695	0.26	0.66	0.4			154%		
696	0.04	0.4	0.36			900%		
697	0.39	0.47	0.08			21%		
698	0.76	0.82	0.06			8%		
699	0.41	0.41	0			0%		
700	0.27	0.34	0.07			26%		
701	0.65	0.67	0.02			3%		
702	0.59	0.78	0.19			32%		
703	0.25	0.46	0.21			84%		
704	0.26	0.26	0	0.17	0.21	0%		
705	0.52	0.77	0.25			48%		
706	-0.3	-0.48	-0.18					
PORT SHELTON JETTIES								
707	-1.2	-1.05						
708	0.11	0.62	0.51			464%		
709	0.71	0.83	0.12			17%		
710	-0.04	0.55	0.59			1475%		
711	0.33	0.41	0.08			24%		
712	0.64	0.75	0.11			17%		
713	0.48	0.73	0.25			52%		
714	0.61	0.79	0.18			30%		
715	0.39	0.61	0.22			56%		
716	0.14	0.22	0.08			57%		
717	0.18	0.31	0.13			72%		
718	0.27	0.33	0.06			22%		
719	0.64	0.72	0.08	0.20	0.17	13%		
720		0.45						
721	-0.49	-0.06	0.43					
HOLLAND ARROW HEAD JETTIES								
722	-0.04	-0.04	0					
723	0.66	0.53	-0.13			-20%		
724	0.48	0.58	0.1			21%		
725	0.45	0.66	0.21			47%		
726	0.56	0.77	0.21			38%		
727	0.59	0.45	-0.14	0.14	0.19	-24%		
728	0.27	0.46	0.19			70%		
729	0.34	0.77	0.43			126%		
730	0.33	0.57	0.24			73%		
731	-0.27	0.12	0.39					
732	-1.46	-0.65	0.81					
SAUGATUCK JETTIES								
733	-0.68	0.03						
734	0.31	0.55	0.24			77%		
735	0.34	0.59	0.25			74%		
736	0.16	0.28	0.12	0.20	0.07	75%		
AVG.	0.44	0.62	0.19					

0.44 m/yr versus 0.62 m/yr from 1938 to 1988/'89. The SVRR for the individual reaches over the longer period ending in 1988/'89 were greater for 38 of the 42 comparisons, with increases ranging from a few percentages points to orders of magnitude increases in

erosion. For example, the SVRR for Reach 710 recorded accretion for the 1938 to 1970/'73 period, while an erosion rate of 0.55 m/yr was recorded from 1938 to 1988/'89.

A review of the long term recorded monthly mean water levels for Lake Michigan are presented in Figure 5.2 and provide insight to the dramatic increase in erosion rates for the sandy reaches from 682 to 736. The 1938 to 1970/'73 period included lows in the late 1930s average levels 1940s, and high lake levels in the early 1950s and 1960s. The 1938 to 1988/'89 rates experienced the same lake levels trends, with the addition of two decades of very high lake levels in the 1970s and 1980s. Significant cross-shore profile adjustment would have occurred over this additional 15 year period of high lake levels, as the back beach and foredune is eroded and sand is transported in an offshore direction and deposited in sand bars.



**Figure 5.2 Lake Michigan Monthly Mean Water Levels**

In the long term, the sandy reaches in Ottawa and Allegan Counties erode due to gradients in longshore sediment transport. The average SVRR of 0.44 m/yr from 1938 to 1970/'73 appears to be representative of the long term erosion potential due to gradient related erosion, as the temporal period covers a wide range of low, average and high lake levels. The rates from 1938 to 1988/'89 however, are heavily biased by two decades of high lake levels at the end of the temporal period. The result is a significant cross-shore profile adjustment and higher SVRR for the sandy reaches. The average increase in the SVRR between the two temporal periods (0.19 m/yr) can be attributed to the cross-shore profile adjustment associated with high lake levels.

#### *5.1.2.2 Sediment Budget Inputs from Dune Erosion*

Inputs to the sediment budget from the erosion of the sandy dunes in Ottawa and Allegan County were computed with the Sediment Budget Module. The results are summarized in Table 5.2. The average bluff height was extracted from the 1999 topographic mapping

**Table 5.2**  
**Sediment Budget Inputs From Bluff/Dune Erosion (1970/'73 SVRR)**

Reach	Net LST Direction	Avg. Bluff Height (m)	Base Elevation (m)	SVRR (m/yr)	Input per Reach (m³/yr)	Inputs per Sub-Cell (m³/yr)	
682	N	10	0	0.3	3000	28,176	
683	N	10.8	0	0.49	5292		
684	N	12	0	0.61	7320		
685	N	12.9	0	0.43	5547		
686	N	9.5	0	0.52	4940		
687	N	6.7	0	0.31	2077		
688		7.1	0	0.09			
GRAND HAVEN JETTIES							
689		4.4	0				
690	N	14.4	0	0.29	4176	118,582	
691	N	20.5	0	0.55	11275		
692	N	16	0	0.62	9920		
693	N	14.8	0	0.56	8288		
694	N	25.2	0	0.3	7560		
695	N	25.7	0	0.26	6682		
696	N	25.6	0	0.04	1024		
697	N	20	0	0.39	7800		
698	N	18	0	0.76	13680		
699	N	15.5	0	0.41	6355		
700	N	10	0	0.27	2700		
701	N	12	0	0.65	7800		
702	N	24.2	0	0.59	14278		
703	N	22	0	0.25	5500		
704	N	18.4	0	0.26	4784		
705	N	13	0	0.52	6760		
706		15	0	-0.3			
PORT SHELDON JETTIES							
707		19.2	0	-1.2			
708		22.8	0	0.11	2508	73,662	
709		21	0	0.71	14910		
710		16.5	0	-0.04			
711		15.6	0	0.33	5148		
712		15.3	0	0.64	9792		
713		13.5	0	0.48	6480		
714		17.1	0	0.61	10431		
715		14.5	0	0.39	5655		
716		12	0	0.14	1680		
717		11.4	0	0.18	2052		
718		12.2	0	0.27	3294		
719		18.3	0	0.64	11712		
720		24.3	0		0		
721		23	0	-0.49			
HOLLAND ARROW HEAD JETTIES							
722	S	3	0	-0.04			
723	S	6.5	0	0.66	4290	82,939	
724	S	11.6	0	0.48	5568		
725	S	27.6	0	0.45	12420		
726	S	29.6	0	0.56	16576		
727	S	32.9	0	0.59	19411		
728	S	26.1	0	0.27	7047		
729	S	26.9	0	0.34	9146		
730	S	25.7	0	0.33	8481		
731	S	22.2	0	-0.27			
732	S	6	0	-1.46			
SAUGATUCK JETTIES							
733	S	8	0	-0.68			
734	S	6	0	0.31	1860	6,860	
735	S	10	0	0.34	3400		
736	S	10	0	0.16	1600		
Total						310,219	

and a base elevation of 0.0 m was assumed (i.e. LWD). The 1938 to 1970/'73 SVRR

were used for the calculation, since they were assumed to be most representative of the long term, gradient driven, erosion rate for this reach of Lake Michigan.

The equation for the sediment input is:

$$\text{Bluff Inputs} = \text{Dune Elevation (m)} * 1,000 \text{ m} * \text{SVRR (m/yr)}$$

The annual input of sand and gravel to the sediment budget is estimated at approximately 310,000 m<sup>3</sup>/yr based on the 1938 to 1970/'73 SVRR. For comparison purposes, the input volume due to dune erosion increases to 470,000 m<sup>3</sup>/yr when the 1938 to 1988/'89 SVRR are used for the calculation. This discrepancy highlights the critical importance of accurate reach specific long term erosion rates that are not biased by lake levels when used for sediment budget calculations.

#### *5.1.2.3 Inputs from Harbor Dredging and Beach Nourishment*

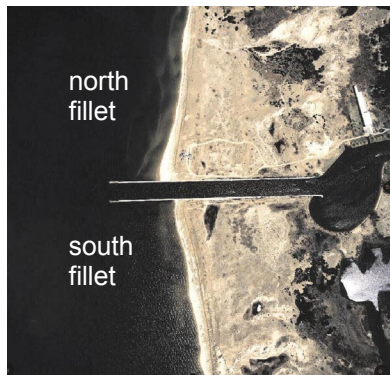
A sample of the database on harbor dredging and beach nourishment was provided in Table 4.3 for Grand Haven. For the harbors in Ottawa and Allegan County, most of the sediment dredged from the navigation channels is placed on the adjacent fillet beaches. Therefore, beach nourishment from a maintenance dredging program is not counted in the sediment budget module since the material is simply being relocated in the littoral zone (assumes no significant inputs from rivers). However, when the beach nourishment comes from an upland source, such as the 1986 project at Grand Haven, the nourishment volume is included in the sediment budget calculations.

#### *5.1.2.4 Accumulation of Sediment in the Fillet Beaches*

Sediment accumulation has occurred in the fillet beaches associated with the harbors at Grand Haven, Port Sheldon, Holland, and Saugatuck from Reach 682 to 736. The fillet beaches represent sediment sinks and the total volume of accumulation is required for the sediment budget calculations. Detailed shoreline mapping at Saugatuck is discussed, along with a preliminary estimate of the sediment volume in the fillet beaches at the four harbors.

An aerial photograph of the harbor jetties at Saugatuck is provided in Figure 5.3. Historic shoreline mapping was available from the initial construction drawings for the project dated 1904 and an intermediate period (1947). These historic shoreline positions, in addition to the 1999 topographic mapping provided data to calculate annualized shoreline change rates (SCR) for the fillet beaches at Saugatuck. The results are summarized in Table 5.3. The long term accretion rate for the north fillet beach is 1.93 m/yr, from 1904 to 1999. Interestingly, when the SCR are reviewed for the two periods, 1904 to 1947 and 1947 to 1999, a significant reduction in the accretion rate has occurred in the last 50 years

(2.79 m/yr vs. 1.21 m/yr). A similar trend was found for the south fillet beach (Table 5.3).



**Figure 5.3**

**Table 5.3**  
**Shoreline Change Rates for Saugatuck Fillet Beaches**

Annualized Shoreline Change Rate (m/yr)	South Jetty Fillet Beach	North Jetty Fillet Beach
1904 to 1947	2.30	2.79
1947 to 1999	1.29	1.21
1904 to 1999	1.75	1.93

The long term SCR for the fillet beaches at Saugatuck highlights the importance of temporal scale for the analysis of erosion and sedimentation rates on the Great Lakes. The processes and trends are seldom linear, and results must always be assessed based on the temporal scale of the data and the influence of time on the physical processes. At Saugatuck, the SCR suggest the fillet beaches are reaching capacity, which may result in more sediment available bypassing (and possibly sedimentation in the new channel).

Detailed historic mapping was not reviewed for the three remaining harbors. However, the history of the jetty construction is summarized in Table 5.4 (where available). A preliminary analysis of sediment accumulation in the fillet beaches was completed for all four harbors based on existing topographic and bathymetric information. The sediment volumes are presented in Table 5.4 and range from approximately 1 million m<sup>3</sup> at Grand Haven and Saugatuck, to only 360,000 m<sup>3</sup> at Holland. The low accumulation rates at Holland are attributed to the longshore sediment transport patterns in Ottawa and Allegan Counties, which are discussed in Section 5.1.2.6.

**Table 5.4**  
**Estimates of Fillet Beach Accumulation Since Jetty Construction (*preliminary*)**

	Authorized (year)	First Construction (year)	Completion (year)	North Fillet (m <sup>3</sup> )	South Fillet (m <sup>3</sup> )	Total (m <sup>3</sup> )
Grand Haven	1866	1867	1949	653,929	439,083	1,093,012
Port Sheldon	not Federal			480,828	318,122	798,950
Holland	1852	1868	1957	265,750	95,573	361,323
Saugatuck	1896	1904	1911	571,629	403,477	975,106

#### 5.1.2.5 Lake Bed Deposition at Harbors

Lake bed deposition in the vicinity of the harbor structures also represents a sink for the sediment budget in Ottawa and Allegan Counties. The jetties can represent a partial barrier to longshore sediment transport, resulting in lake bed deposition. The 1948 to 1999 lake bed comparison at Holland is presented in Figure 5.4, which documents accumulations in Reaches 721 and 722, which correspond to the north and south fillet beaches respectively. In addition to the surface of change in Figure 5.4, the GIS also calculates volumes of erosion and accretion, which are then input to the sediment budget module. A similar comparison was generated at Port Sheldon. However, the absence of the 1999 SHOALS coverage at Saugatuck and Grand Haven precluded the generation of a historic to recent lake bed comparison for these harbors.

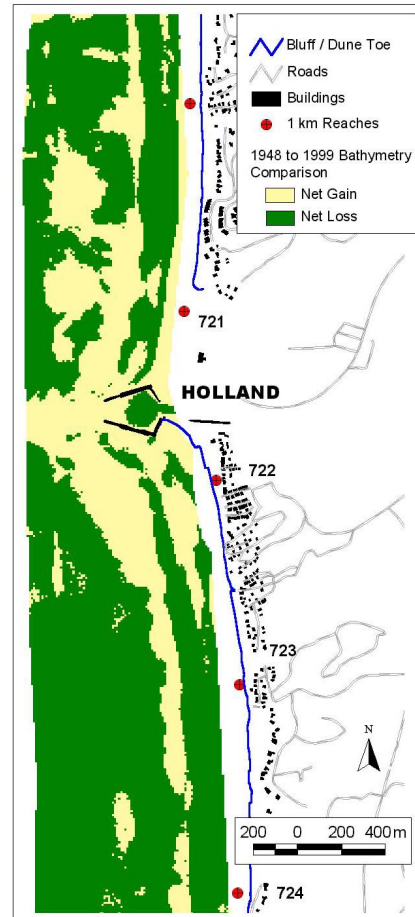


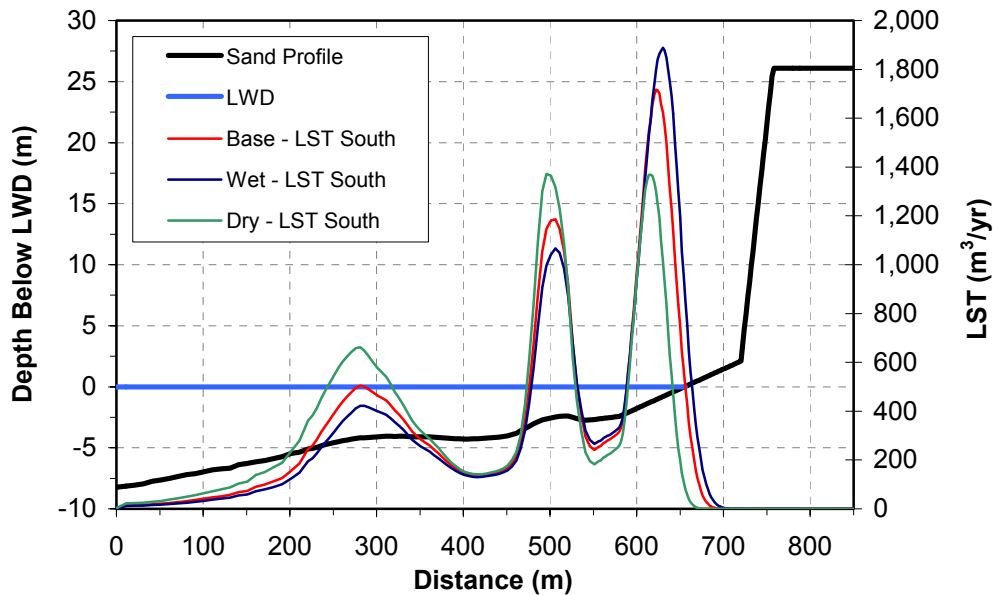
Figure 5.4 Holland

#### 5.1.2.6 COSMOS Longshore Sediment Transport Modeling

The ESWave module was used to generate a 50 year nearshore wave climate for the three LMPDS lake level scenarios from reach 0682 in the north to reach 0736 in the south. The GIS Profile Tool and the COSMOS module in the UI were used to generate an input menu for the model and run the simulations.

A sample of the longshore sediment transport results for Reach 0728 are presented graphically in Figure 5.5 to highlight the capabilities of COSMOS to: 1) model the volume of longshore sediment transport; 2) predict the cross-shore distribution of LST; and 3) quantify the effects of lake levels on the magnitude and distribution of LST. The northward directed component of LST is plotted in Figure 5.5 for the three LMPDS lake level scenarios. The transport across the outer bar is greatest for extreme dry scenario, which features the lowest lake levels. Conversely, in the swash zone, the LST rate is higher for the extreme wet scenario, which features the highest lake levels. Interestingly,

although the distribution and magnitude of the LST varies across the bars and swash zone for the three scenarios, the total volumes are very similar.

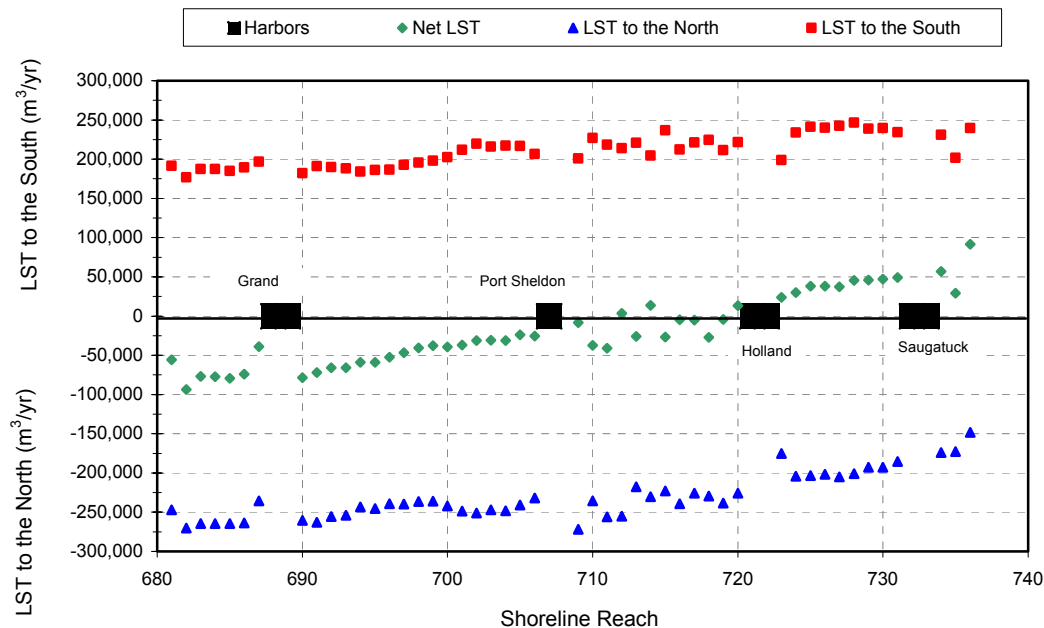


**Figure 5.5 Average Annual LST Volume and Distribution for Reach 0728**

The results of the longshore sediment transport modeling for Reaches 681 to 736 are presented in Figure 5.6 for the base case lake level conditions (i.e. similar wet and dry). For each reach, the average annual northward and southward directed transport components are plotted, along with the net transport volume. Several key observations are noted based on the modeling results in Figure 5.6:

1. The shore from Port Sheldon to Holland represents a nodal point for longshore sediment transport along the south eastern shore of Lake Michigan;
2. North of Port Sheldon, the net direction is to the north and the gradient in LST increases from 25,000 to approximately 75,000 m<sup>3</sup>/yr;
3. South of Holland, the net transport direction is to the south, and increases from 25,000 to 100,000 m<sup>3</sup>/yr;
4. The nodal point between Holland and Port Sheldon explains the relatively small fillet beaches at these two harbors, since the net direction for LST is directed away from the fillet beaches;

5. The net transport rates are small compared to the overall gross transport volumes for the shoreline (i.e. generally less than 20%). For example, although the net transport direction between Holland and Saugatuck is to the south, there will be significant storm events with incident waves from the south west that are capable of transporting sediment to the south fillet beach at Holland.

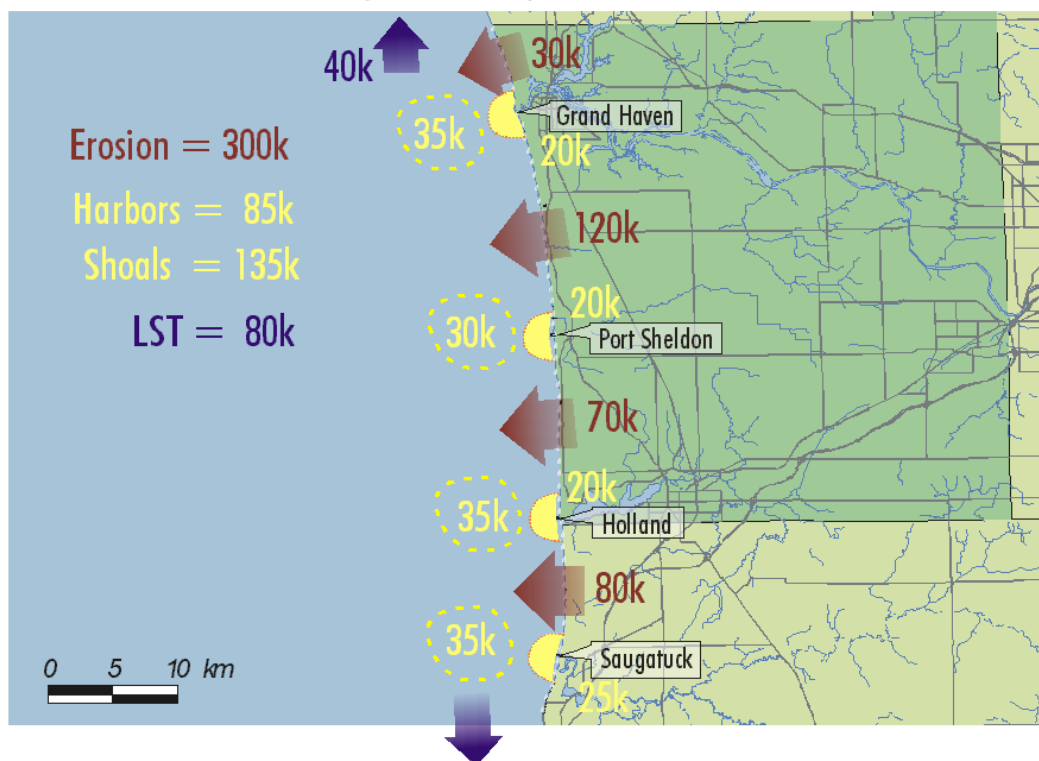


**Figure 5.6 COSMOS Longshore Sediment Transport Estimates – Base Case Scenario**

### 5.1.3 Application of the Sediment Budget Module

Once the coastal database was populated with the necessary data on sediment sources, sinks and rates of longshore sediment transport, the FEPS was used to close the historic sediment budget from reaches 682 to 736. The results for the regional sediment budget are summarized in Figure 5.7 for the 1938 to 1970/'73 historic erosion rates. The primary input of new sediment is from bluff erosion and is estimated at 300,000 m<sup>3</sup>/yr. Based on the sediment transport modeling summarized in Figure 5.6, the net loss of sediment due to gradients in LST is 80,000 m<sup>3</sup>/yr. Sediment accumulation in the vicinity of the harbors was estimated at 85,000 m<sup>3</sup>/yr and includes both fillet beach and lake bed deposition.

The initial runs of the sediment budget with the above input variables failed to account for deposition totaling 135,000 m<sup>3</sup>/yr. There are several possible reasons for the unaccounted sediment: 1) inputs from bluff erosion are too high; 2) additional lake bed deposition occurs offshore of the harbor which is not counted due to the limits of the 1999 SHOALS coverage; and 3) losses at the northern and southern boundaries of the sediment budget are higher than 40,000 m<sup>3</sup>/yr.



**Figure 5.7 Ottawa and Northern Allegan Counties Regional Sediment Budget**

It is possible that the 135k discrepancy in deposition is attributed to one or all of the three above mentioned scenarios. Without further data on historic recession rates and existing lake bed bathymetry offshore of the harbors, it was not possible to close the sediment budget. Deposition in offshore shoals was considered the most likely explanation and the sediment budget summary in Figure 5.7 was labeled accordingly.

#### **5.1.4 Predictions for the LMPDS Lake Level Scenarios**

The results of the sediment budget application in the FEPS to predict future shoreline position for the three LMPDS lake level scenarios is discussed. Also, the results of a preliminary investigation into the influence of cross-shore lake levels effects on sandy shore erosion is outlined.

##### **5.1.4.1 Sediment Budget Results**

In theory, once the historic sediment budget is closed (i.e. the volume of all sources and sinks is equal), the module can be used to test the influence of the LMPDS lake level scenarios on future erosion rates and “what if” scenarios for regional sediment management, such as improved dredging and beach nourishment practices. Assuming

that the assumptions about deposition in the shoals offshore of the harbors was correct (refer to Figure 5.7), the sediment budget module was used to test the influence of the three LMPDS scenarios on future erosion and deposition patterns in the sandy reaches of Ottawa and Allegan Counties.

The first variable in the sediment budget that was investigated was rates of longshore sediment transport. Recall from Section 3.1.1 of the report that the identical 50 year wave climate and ice conditions were assigned to each of the three LMPDS lake level scenarios. Therefore, in the COSMOS simulations the only variable in the hourly time series that will differ between the three scenarios is the lake level.

The influence of the LMPDS lake level scenarios on LST rates was investigated for a section of the study boundaries from Holland to Saugatuck (0723 to 0736). The north and south components of the annual longshore sediment transport volumes, along with the net transport, are listed in Table 5.5. The results for the 15 reaches were surprisingly similar. The net direction of longshore sediment transport is to the south and ranges from 20,000 to 90,000 m<sup>3</sup>/yr.

**Table 5.5**  
**Comparison of COSMOS LST Estimates for the LMPDS Lake Level Scenarios**

Reach	Base Case			Extreme Wet			Extreme Dry		
	LST North	LST South	Net	LST North	LST South	Net	LST North	LST South	Net
722	-216,433	215,142	-1,290	-216,869	216,018	-850	-215,823	214,172	-1,651
723	-175,297	199,021	23,723	-167,941	191,909	23,968	-185,828	210,505	24,678
724	-204,006	234,069	30,063	-203,311	233,530	30,219	-204,972	234,825	29,853
725	-203,440	241,375	37,935	-202,260	240,584	38,324	-204,762	242,503	37,741
726	-201,842	239,861	38,019	-201,011	239,352	38,341	-202,674	240,418	37,743
727	204,897	242,317	37,421	-204,909	242,985	38,076	-204,403	241,347	36,944
728	-200,955	246,512	45,557	-200,154	246,545	46,391	-201,378	245,971	44,593
729	-192,884	238,760	45,876	-192,761	239,131	46,369	-192,817	238,060	45,243
730	-192,595	239,518	46,932	-192,494	239,729	47,234	-192,770	239,341	46,571
731	-185,340	234,379	49,039	-184,667	234,077	49,410	-186,753	235,798	49,045
732	-166,264	227,308	61,045	-165,904	227,393	61,489	-167,234	229,417	62,183
733	-176,950	227,054	50,104	-173,943	223,658	49,715	-180,671	231,074	50,403
734	-174,011	230,872	56,861	-171,024	227,025	56,001	-178,006	235,658	57,652
735	-172,557	201,536	28,980	-170,524	197,593	27,070	-174,190	204,889	30,699
736	-148,112	239,812	91,700	-145,895	236,271	90,377	-151,439	244,046	92,607

Table 5.6 lists differences between the three scenarios on a km by km basis for the 12 reaches not influenced by the harbor jetties. The percentage difference in the net transport rates between Base and Wet Scenario averages only 1.6%. Between the Base and Dry, the difference increases slightly to 1.7%. When the net transport rates between the Wet and Dry Scenarios are compared, the average difference for all reaches is only 3.1%. These percentages are small and within the error range of the COSMOS model.

Therefore, based on the results summarized in Tables 5.5 and 5.6, there is no measurable difference in the rates of longshore sediment transport between the three LMPDS lake

level scenarios. Since LST rates and gradients are the primary driving forces behind exchanges in the sediment budget (i.e. between reaches), the rates of erosion and sedimentation are almost identical for all three scenarios. Consequently, the estimates of future shoreline position from the sediment budget module at 20, 35 and 50 years for the sandy reaches of Allegan and Ottawa County are identical (based on transport gradients).

**Table 5.6**  
**Comparison of COSMOS LST Estimates for Three LMPDS Scenarios**

Reach	Base/Wet (% difference)	Base/Dry (% difference)	Wet/Dry (% difference)
722	fillet beach	fillet beach	fillet beach
723	1.0%	4.0%	3.0%
724	0.5%	0.7%	1.2%
725	1.0%	0.5%	1.5%
726	0.8%	0.7%	1.6%
727	1.7%	1.3%	3.0%
728	1.8%	2.1%	3.9%
729	1.1%	1.4%	2.4%
730	0.6%	0.8%	1.4%
731	0.8%	0.0%	0.7%
732	fillet beach	fillet beach	fillet beach
733	fillet beach	fillet beach	fillet beach
734	1.5%	1.4%	2.9%
735	6.6%	5.9%	13.4%
736	1.4%	1.0%	2.5%
<b>Average</b>	1.6%	1.7%	3.1%

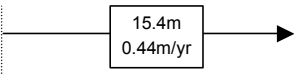

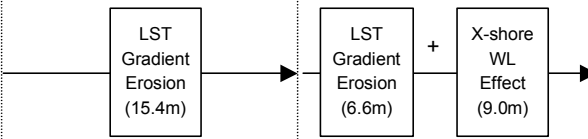
#### 5.1.4.2 Cross-shore Effect of Lake Levels

Based on the results of the sediment budget application for the three LMPDS lake level scenarios discussed in Section 5.1.4.1, the future top of bank lines in Ottawa and Allegan Counties would be identical. However, this finding is at odds with the observations on SVRR discussed in Section 5.1.2.1 that documented a significant increase in erosion rates during the high lake level periods in the mid 1970s and 1980s. Consequently, a limited preliminary investigation was completed to assess the relationship between lake levels and erosion rates in Ottawa and Allegan County.

The SVRR for Ottawa and northern Allegan County were presented in Table 5.1. The average SVRR for the two time periods, 1938 to 1970/'73 and 1938 to 1988/89, are further analyzed in Table 5.7. Since the measurement period commences in the same year (1938) and likely based on the same aerial photographs, there was a unique opportunity to isolate the influence of the high lake levels in the mid 1970s and 1980s.

The average for all the reaches from 1938 to 1970/'73 was 0.44 m/yr, which translates to 15.4 m of top of dune erosion over the 35 year period (Table 5.7). Since this temporal period included a good mixture of low, average and high lake levels, the SVRR are assumed to be representative of the long term gradient driven erosion rate. In other words, the erosion is attributed to gradients in longshore sediment transport along the shoreline and not significantly influenced by changes in lake levels over the 35 year period.

**Table 5.7**  
**Interpretation of Long Term SVRR in Ottawa and Allegan County**

Temporal Period	Avg. SVRR (m/yr)	Total Erosion (m)	Total Erosion for the Two Periods				
			1938	(35yrs)	1973	(15yrs)	1988
1938 to 1970/'73	0.44	15.40					
1938 to 1988/'89	0.62	31.00					
Gradient Erosion vs. Cross-shore Effects							

The 1938 to 1988/'89 average SVRR was 0.62 m/yr (Table 5.1). Since the average SVRR over the 50 year period was 0.62 m/yr, the total horizontal retreat of the top of dune was 31.0 m. As discussed above, the total erosion distance for the 1938 to 1973 period was 15.4 m. Therefore, over the 15 year period from 1973 to 1988, the top of dune retreated a total 15.6 m for an annualized shoreline change rate of 1.04 m/yr ( $15.4 + 15.6 = 31.0$  m).

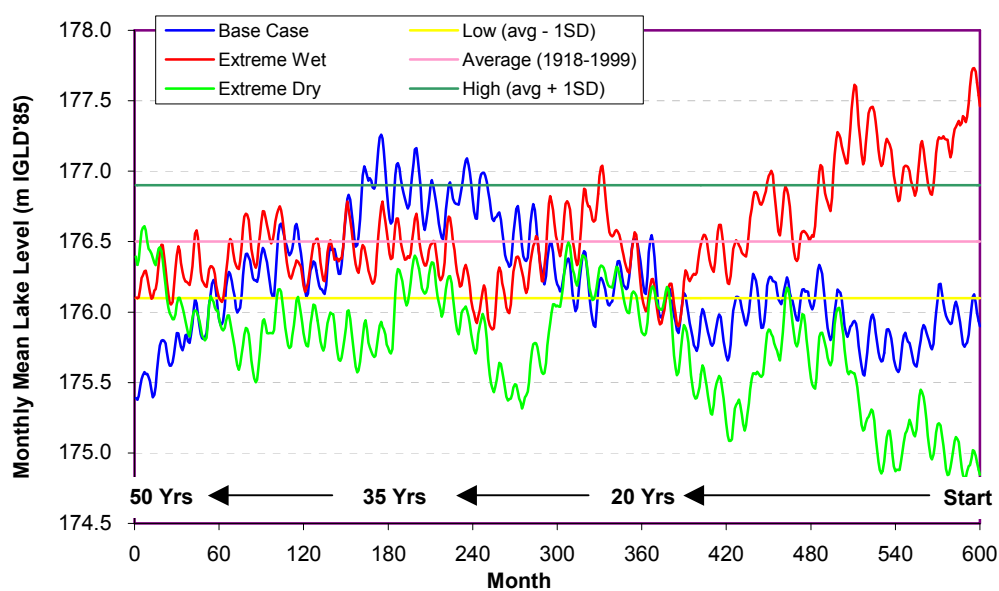
The total erosion from 1973 to 1988 is further analyzed. Based on the assumption that 0.44 m/yr is the background gradient driven erosion rate, the top of dune retreat would have been 6.6 m/yr with a mixture of high and low lake levels. Therefore, the remaining 9.0 m of retreat ( $15.6 - 6.6 = 9.0$  m) must be attributed to cross-shore erosion processes due to the increased lake levels in the mid 1970s and 1980s, as outlined in Table 5.7.

Based on the above finding of cross-shore lake level induced erosion and other research related to lake levels (i.e. Hands, 1979), the following set of rules was developed to add a correction factor to the future shoreline estimates from the sediment budget:

1. When extreme low lake levels in the time series are followed by a period of very high lake levels, a correction band of 10 m is added to the top of bank retreat estimate based on the sediment budget prediction;
2. Conversely, when a period of sustained high lake levels is followed by extreme low lake levels, a 10 m lakeward correction is added to the predicted sediment budget dune crest line;

- When average lake levels are followed by high water levels, a 5 m landward correction band is added. The correction band is 5 m lakeward when average levels are followed by low water levels in the time series record.

As an example, the 50 year monthly mean lake levels for the LMPDS scenarios are presented in Figure 5.9. The three horizontal lines plotted on Figure 5.9 represent average, high and low lake levels based on the long term recorded monthly means for Lake Michigan. The high and low elevations are equal to the average (176.5 m) plus and minus one standard deviation unit (respectively). When the monthly lake levels are beyond the range defined by  $\pm$  one standard deviation unit, the levels are considered to be extreme.



**Figure 5.9 LMPDS Scenarios and Long Term Average Monthly Lake Level**

For the FEPS applications in Ottawa and Allegan Counties, the time series lake level data was run backwards, beginning with month 600 and ending with month 1. The objective was to incorporate the extreme high and low lake levels that occur in months 480 to 600 at the onset of the modeling. The five year average lake level prior to the spring of 1999 was slightly above the long term average. However, for the last six months prior to the photography, the lake levels were decreasing steadily to levels below average. Therefore, the mapping derived from the 1999 spring photography were assumed to be representative of average lake level conditions. Therefore, the starting point for the scenario predictions was average. Two examples are provided to illustrate the correction:

- After 20 years of time series data, run backwards (refer to Figure 5.9), the extreme dry scenario remains in the low range. Therefore, in addition to the gradient erosion rate, a 5 m lakeward correction is applied to the 20 year sediment budget top of dune line;

2. Although the extreme wet scenario begins with high lake levels for the 20 year period from month 600 to 480 (when run backwards), months 480 to 360 fall in the average range. Therefore the starting and ending lake levels for the 20 year prediction period are both average and no correction is applied.

Table 5.8 summarizes the correction band for the three LMPDS scenarios. As noted above, the time sequence was run backwards from month 600 to 1, as depicted in Figure 5.9. At the 20, 35 and 50 year intervals, the predicted dune crest line may have either a 5 m landward, 5 m lakeward correction band, or no correction.

**Table 5.8**  
**Correction Band for LMPDS Scenarios - Sandy Reaches**

LMPDS Scenario	20 Year Top of Bank	35 Year Top of Bank	50 Year Top of Bank
Base Case	5m lakeward	5m landward	5m lakeward
Extreme Wet	<i>no correction</i>	<i>no correction</i>	<i>no correction</i>
Extreme Dry	5m lakeward	5m lakeward	5m lakeward

The above listed rules are very general in nature and were developed based on the preliminary analysis of the relationship between lake levels and shore erosion for sandy reaches. Further investigation is necessary to refine the methodology to address cross-shore lake level related shore erosion for the LMPDS lake level scenarios.

#### **5.1.5 Conclusions and Recommendations**

The following list of conclusions and recommendations is provided for the FEPS modeling in Ottawa and northern Allegan Counties:

1. The SVRR appear to record a significant cross-shore lake level induced erosion rate in addition to the long term gradient driven process;
2. Detailed erosion measurements are recommended for multiple decades to further investigate lake level influences on sandy shorelines;
3. The sediment sources and sinks were not equal and consequently the sediment budget did not close for Ottawa and northern Allegan County;
4. Additional work is required to quantify potential sediment sinks, such as the harbor fillet beaches and offshore shoals;

5. Longshore sediment transport rates were almost identical for all three LMPDS lake level scenarios. Therefore, the sediment budget results were identical for all three scenarios;
6. The average SVRR from 1973 to 1988 was 1.04 m/yr, which is a 140% increase over the 1938 to 1973 rate (0.44 m/yr). This finding and the magnitude of the erosion increase (i.e. ~10 m) attributed to the high lake level period were used to develop a preliminary methodology to quantify cross-shore lake level induced erosion and profile recovery;
7. An additional module in the FEPS is required to develop a Bruun Rule type cross-shore profile shift for the sandy reaches to effectively model the impacts of the LMPDS lake level scenarios.

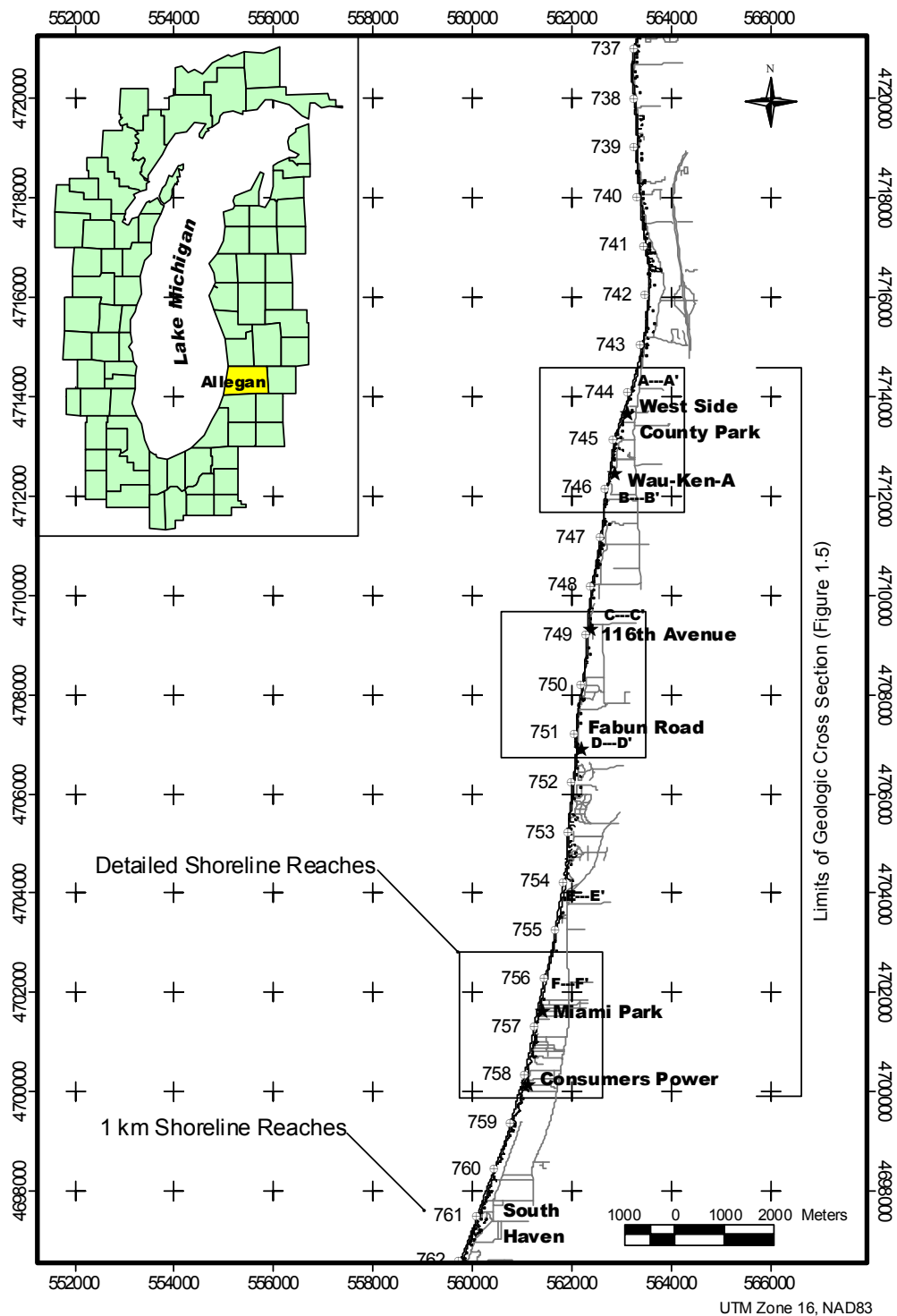
## **5.2 Allegan County – Cohesive Modeling 737 to 762**

Allegan County is located along the south central shore of the lake, in the State of Michigan. Reaches 737 marks the transition from a sandy shore classification to cohesive south of Saugatuck. The shore classification for the 26 reaches is a mixture of composite and homogeneous bluffs, which range in height from 9 to 26 m. A typical photograph of the bluffs is provided in Figure 5.10. The majority of the nearshore lakebed is classified as glacial till with moderate to thick sand cover, with the exception of five reaches in the center of the county which feature a boulder cobble lag lakebed. Refer to Figure 5.11 for a location map.



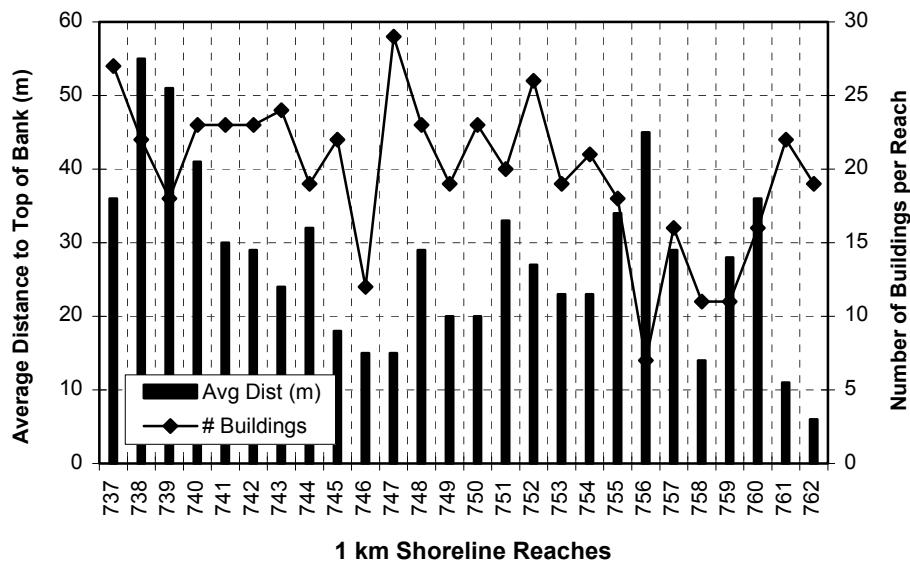
**Figure 5.10 Typical Cohesive Bluff**

There is moderate development along the shoreline, with approximately 500 structures within 100 m of the bluff crest from Reach 737 to 762. Figure 5.12 summarizes the number of buildings adjacent to the top of bank and the average distance on a reach by reach basis. The coastal database is rich for this stretch of cohesive shoreline, including historic bathymetry (1948), a 1999 SHOALS survey, recent topographic mapping collected for the LMPDS and extensive research on the bluff stratigraphy and hydrology by Western Michigan University. Several of the key coastal datasets are discussed, along with significant findings on limitations of existing methods to calculate erosion rates for cohesive bluff sites, a discussion of bluff slope and the treatment of gullies.



**Figure 5.11 Allegheny County Cohesive Reaches (0737 to 0762)**

The results of the COSMOS model calibration are presented, along with the findings of the erosion modeling for the three LMPDS scenarios.



**Figure 5.12 Number of Bluff Top Buildings per Reach**

### 5.2.1 Coastal Data and Analysis

Issues and findings related to the coastal data are discussed, including the SVRR, the detailed historic erosion measurements, and the influence of bluff slope.

#### 5.2.1.1 Single Value Recession Rates

The single value recession rates for Allegan County are summarized in Table 5.9 for two time periods, 1938 to 1973 and 1938 to 1989. The data was generated by the Michigan Department of Environmental Quality. For the 35 year period from 1938 to 1973, the average annualized erosion rate (AER) for the 26 shore reaches was 0.37 m/yr. When the high lake levels of the mid 1970s and 1980s were added to the time series, the average AER from 1938 to 1989 was 0.53 m/yr. At first glance, it would appear that the effect of the high lake levels was an increase in the AER by 0.16 m/yr or 43%. However, as Table 5.9 demonstrates, the effect was significantly greater.

Since both temporal periods begin in 1938, it was possible to isolate the total amount of erosion for the two periods, 1938 to 1973 and 1973 to 1989 (Table 5.9). The average erosion rate from 1973 to 1989 was actually 0.89 m/yr, for a 139% increase over the 1938 to 1973 rate of 0.37 m/yr. These findings highlight the importance of selecting an appropriate temporal scale for the analysis of cohesive shore erosion, which considers both duration and the lake level trends for the period. It is also important to note that the number of erosion transects per 1 km reach ranged from 3 to 8, which corresponds to an

average transect spacing of 125 m to over 300 m. As the following sections will document, this is a very coarse sampling density for the top of bank erosion measurements.

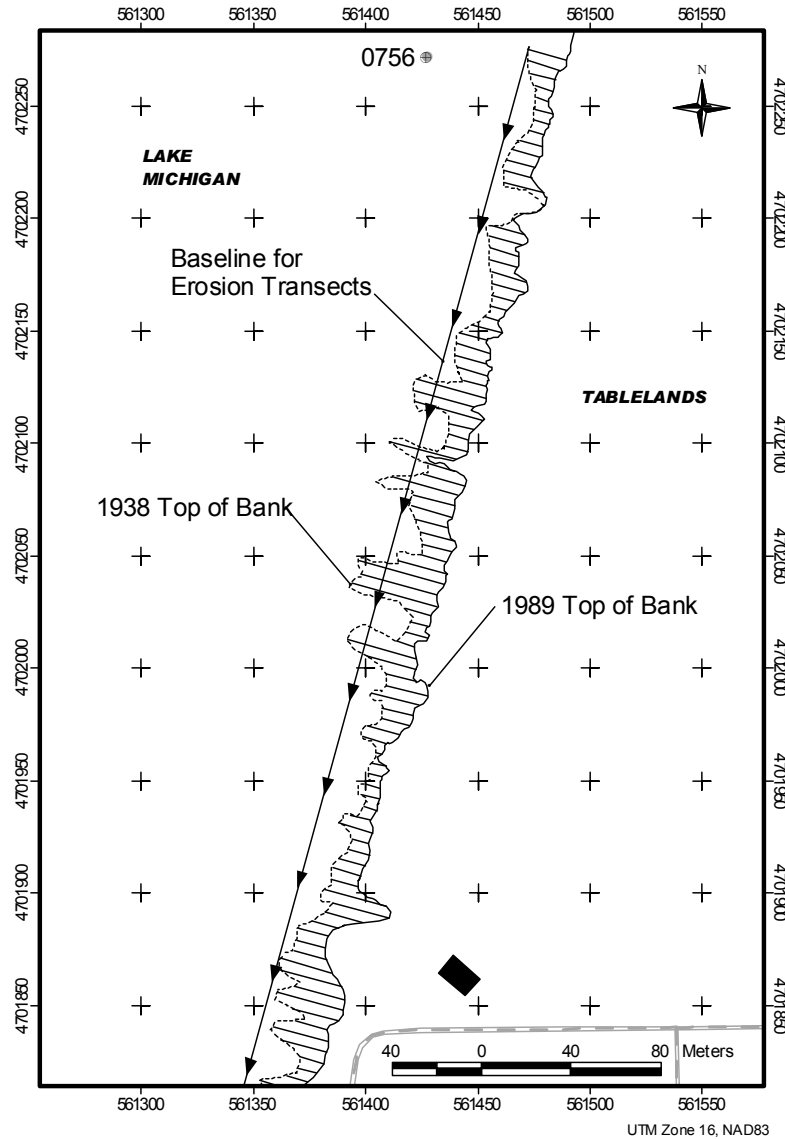
**Table 5.9**  
**SVRR for Allegan County Cohesive Reaches**

SVRR					STATISTICS			
Reach	1938 to 1973 (m/yr)	# of Transects	1938 to 1989 (m/yr)	# of Transects	Total Erosion Dist. 1938 to 1973 (m)	Total Erosion Dist. 1938 to 1989 (m)	1973 to 1989 Erosion Rate (m/yr)	% Increase 1938 to 1973 vs. 1973 to 1989
737	0.35	5	0.43	5	12.3	21.93	0.61	73%
738	0.49	4	0.75	5	17.2	38.25	1.32	169%
739	0.32	6	0.55	5	11.2	28.05	1.05	229%
740	0.29	5	0.30	8	10.2	15.30	0.32	11%
741	0.60	5	0.68	8	21.0	34.68	0.86	43%
742	0.37	4	0.60	5	13.0	30.60	1.10	198%
743	0.33	6	0.54	5	11.6	27.54	1.00	203%
744	0.15	3	0.33	4	5.3	16.83	0.72	383%
745	0.29	7	0.37	7	10.2	18.87	0.55	88%
746	0.23	3	0.24	3	8.1	12.24	0.26	14%
747	0.23	6	0.47	6	8.1	23.97	1.00	333%
748	0.36	4	0.58	4	12.6	29.58	1.06	195%
749	0.36	3	0.82	4	12.6	41.82	1.83	407%
750	0.31	5	0.37	4	10.9	18.87	0.50	62%
751	0.33	4	0.42	4	11.6	21.42	0.62	87%
752	0.41	3	0.55	4	14.4	28.05	0.86	109%
753	0.48	3	0.54	5	16.8	27.54	0.67	40%
754	0.79	4	0.88	6	27.7	44.88	1.08	36%
755	0.83	8	0.90	6	29.1	45.90	1.05	27%
756	0.51	7	0.71	5	17.9	36.21	1.15	125%
757	0.49	5	0.73	4	17.2	37.23	1.26	156%
758	0.23	5	0.50	7	8.1	25.50	1.09	374%
759	0.20	6	0.41	7	7.0	20.91	0.87	335%
760	0.25	8	0.39	6	8.8	19.89	0.70	179%
761	0.11	4	0.30	5	3.9	15.30	0.72	551%
762			0.24	5		12.24		
Average	0.37	4.9	0.52	5.3			0.89	139%

### 5.2.1.2 Detailed Historic Erosion Measurements

Detailed historic bluff mapping was available for nine of the cohesive shoreline reaches in southern Allegan County (Montgomery, 1998) from 1938 to 1989. The location of the reaches is noted on Figure 5.11. The FEPS “Shorettools” were used to calculate detailed top of bank erosion measurements at various transect spacing, ranging from 5 to 200 m intervals, for the 1 km shoreline reaches. An example of the top of bank mapping and erosion transects for Reach 0756 is presented in Figure 5.13.

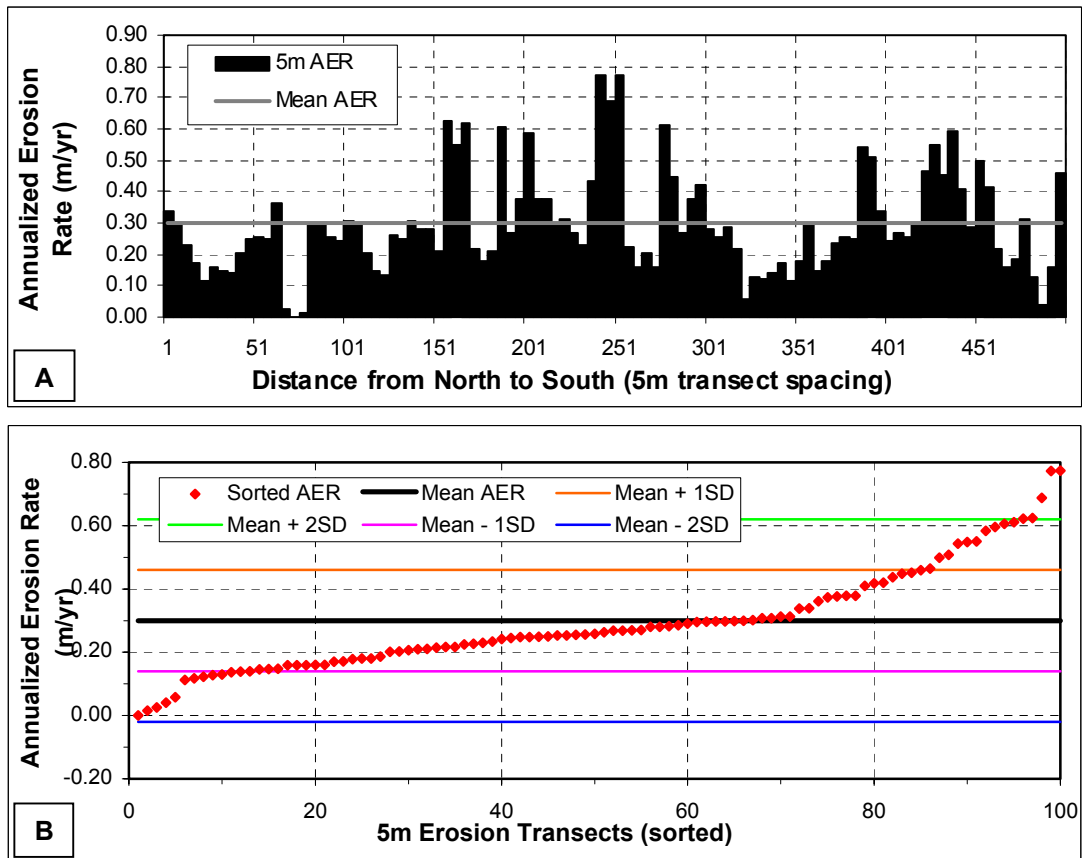
The custom ArcView GIS tools in the FEPS are able to generate detailed erosion measurements quickly and accurately from the information in the coastal database. The transect erosion rates for Reach 0756, based on a spacing of 5 m, are presented in Panel A



**Figure 5.13 1938 and 1989 top of bank mapping and transects**

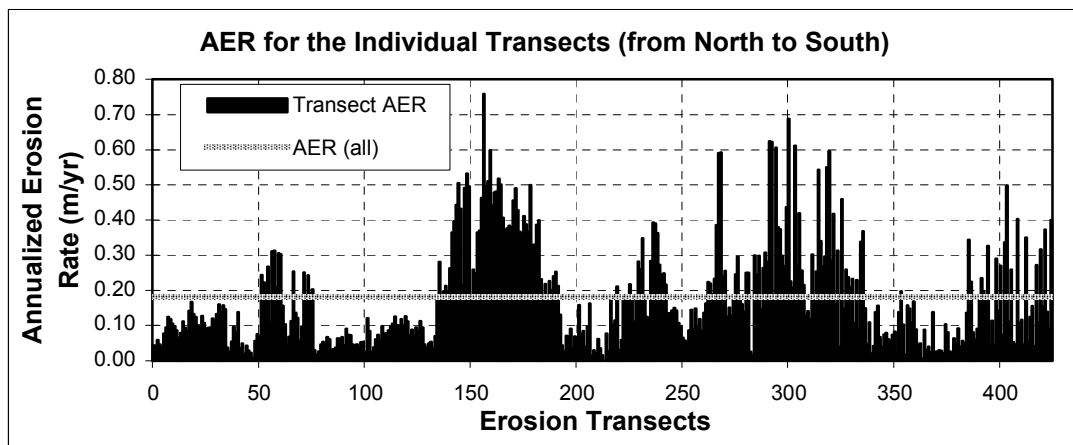
of Figure 5.14 in their order of occurrence (i.e. from north to south). The average annualized erosion rate for all transects is 0.3 m/yr, as noted by the solid gray line. The most interesting observation is the high degree of spatial variability in the transect erosion measurements for Reach 0756.

The annualized erosion rates for the individual transects were also sorted in ascending order in Panel B of Figure 5.14. The mean AER is also plotted as a solid horizontal line, along with the mean  $\pm 1$  and 2 standard deviations. When the individual measurements are sorted, it is clear that very few of the 100 erosion transects are actually close to the mean or average erosion rate of 0.30 m/yr. However, the majority of the AER fall within plus or minus two standard deviation units of the mean.



**Figure 5.14 1938 to 1989 AER for Reach 0756. Transects in Order of Occurrence in Panel A and Sorted in Panel B**

Similar trends in spatial variability of the transect erosion rates were observed in the other detailed shoreline reaches. Figure 5.15 presents the individual transect erosion measurements for all of the nine detailed shoreline reaches, from north to south. The



**Figure 5.15 1938 to 1989 Annualized Erosion Rates for Detailed Reaches**

mean for the entire dataset is presented in Figure 5.15 as the solid gray line. In a similar manor to the results for Reach 0756, the combined nine reach dataset displays extreme spatial variability in annualized erosion rates for both the individual reaches and the entire shore.

The detailed investigation of reach specific annualized erosion rates in Allegan County with the Montgomery data has lead to several important findings and recommendations for measuring top of bank erosion rates for the LMPDS and interpreting work by others:

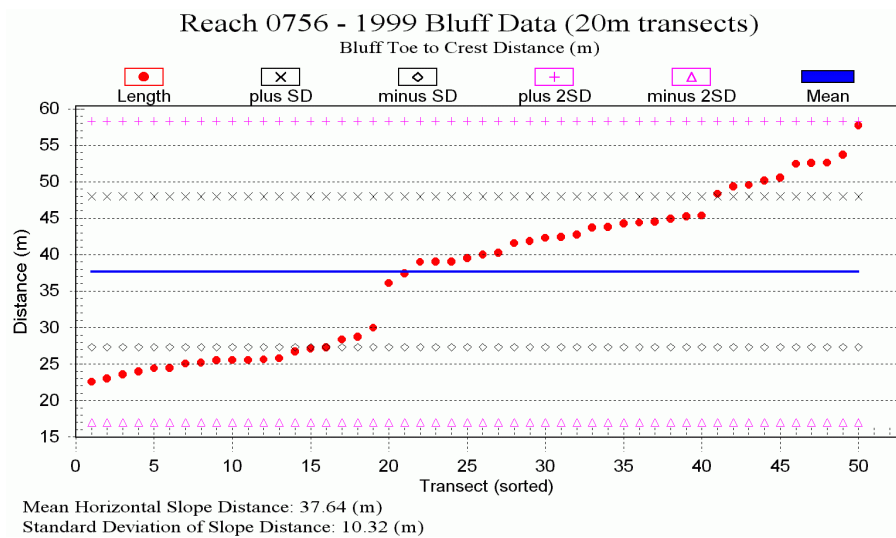
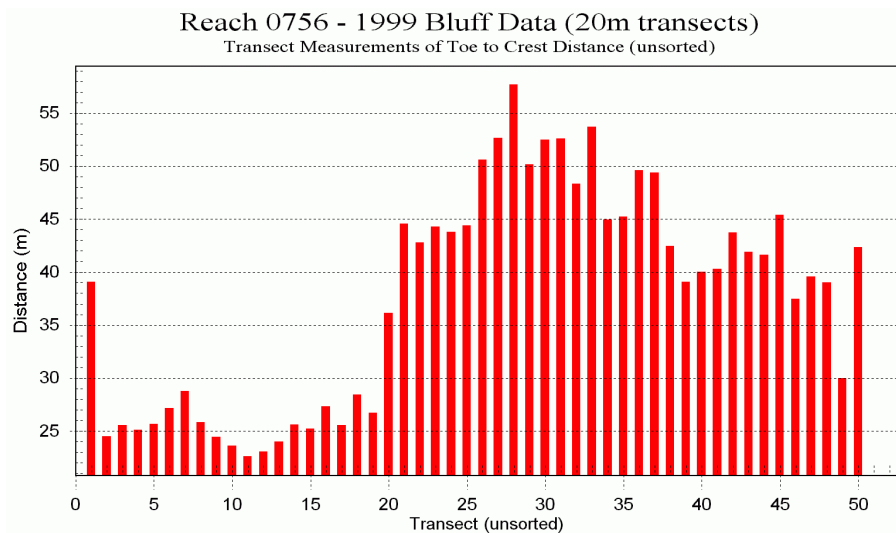
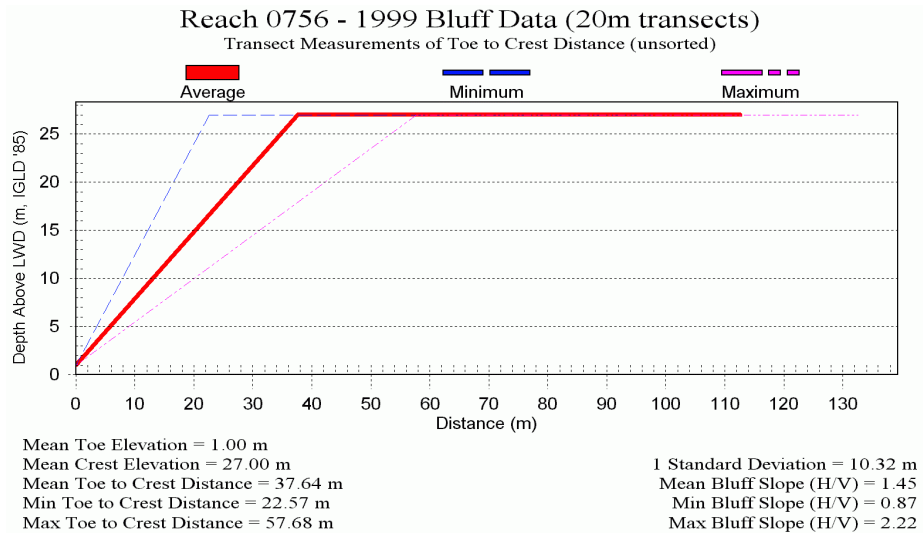
1. Due to the high degree of spatial variability in the transect erosion rates measured within the individual shoreline reaches, it is critical to have a transect spacing of 5 to 20 m. When transect spacing is only every 100 or 200 m, it is possible that the limited sample will only capture the outliers and not generate an accurate erosion measurement;
2. Due to the high degree of spatial variability in the top of bank erosion rates within the 1 km reaches, in addition to reporting the mean or average erosion rate, the standard deviation should also be calculated to provide a measure of the variance in the data;
3. The single value recession rates reported in Table 5.10 were calculated based on an average of 5 erosion transect measurements. Considering the distribution or spread of the erosion measurements about the mean for Reach 0756, the SVRR in the coastal database may not provide a representative long term erosion rate. The results at reach 0756 were representative of the remaining eight detailed reaches.

#### *5.2.1.3 Investigation of Bluff Slope for Reaches 0727 to 0762*

The FEPS “Shorettools” module was also used to investigate the bluff slope characteristics for the cohesive reaches in southern Allegan County. The bluff toe and top of bank mapping was generated from 1999 aerial photographs and provided complete coverage for a continuous 26 km stretch of cohesive shoreline. Once the bluff slope information is extracted from the GIS and stored in the coastal database, the visualization tools in the FEPS UI were used to generate plots and statistics on bluff slope. A sample of the automated graphs generated by the FEPS for Reach 0756 are presented in Figure 5.16.

The top graph in Figure 5.16 presents a 2D plot of the average bluff slope and the two extreme conditions for the reach (steepest and gentlest slope). Statistics are also calculated for additional slope parameters, such as mean toe and top of bank elevation.

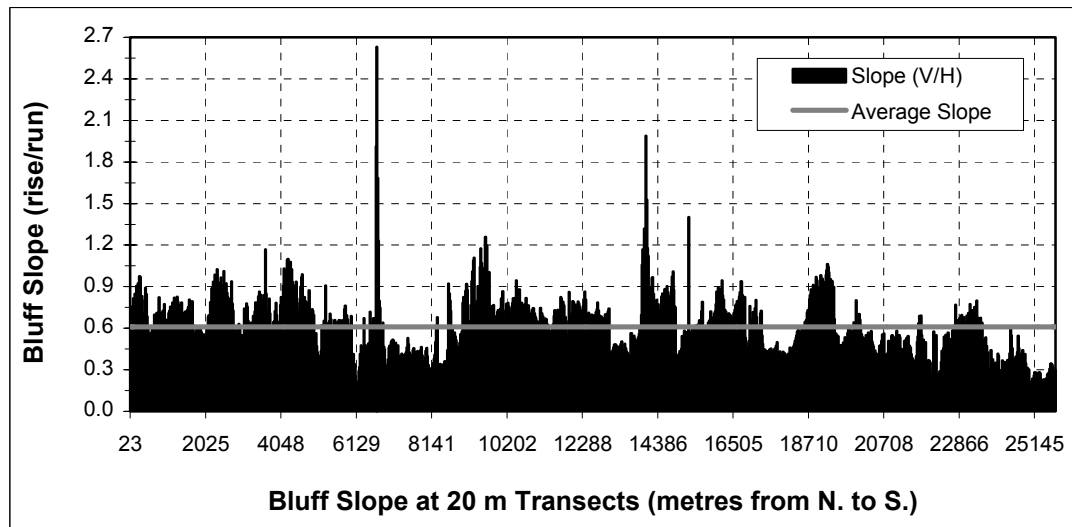
The second and third graphs in Figure 5.16 present the horizontal slope distance, which is a measure of the horizontal distance from the bluff toe to the bluff crest. Since the amount of variability in bluff toe and crest elevations was minimal within the 1 km shoreline reaches, the horizontal slope distance can be considered a good surrogate for



**Figure 5.16 Automated Bluff Slope Graphs Generated with the FEPS UI**

bluff slope. In the bar graph, the horizontal slope distance is plotted in order of occurrence, from north to south, and displays two populations of data. When the slope distance is sorted in ascending order for the third graph in Figure 5.16, the distribution of points looks very similar to the AER for Reach 0756 from 1938 to 1989 (Figure 5.14).

The bluff slope results for Reach 0756 led to a detailed investigation for the remaining 25 cohesive reaches in Allegan County with the FEPS Shoretools. Figure 5.17 summarizes the results of the bluff slope calculations (rise/run) for the entire dataset. The average



**Figure 5.17 Bluff Slope at the Individual Transects, from North to South**

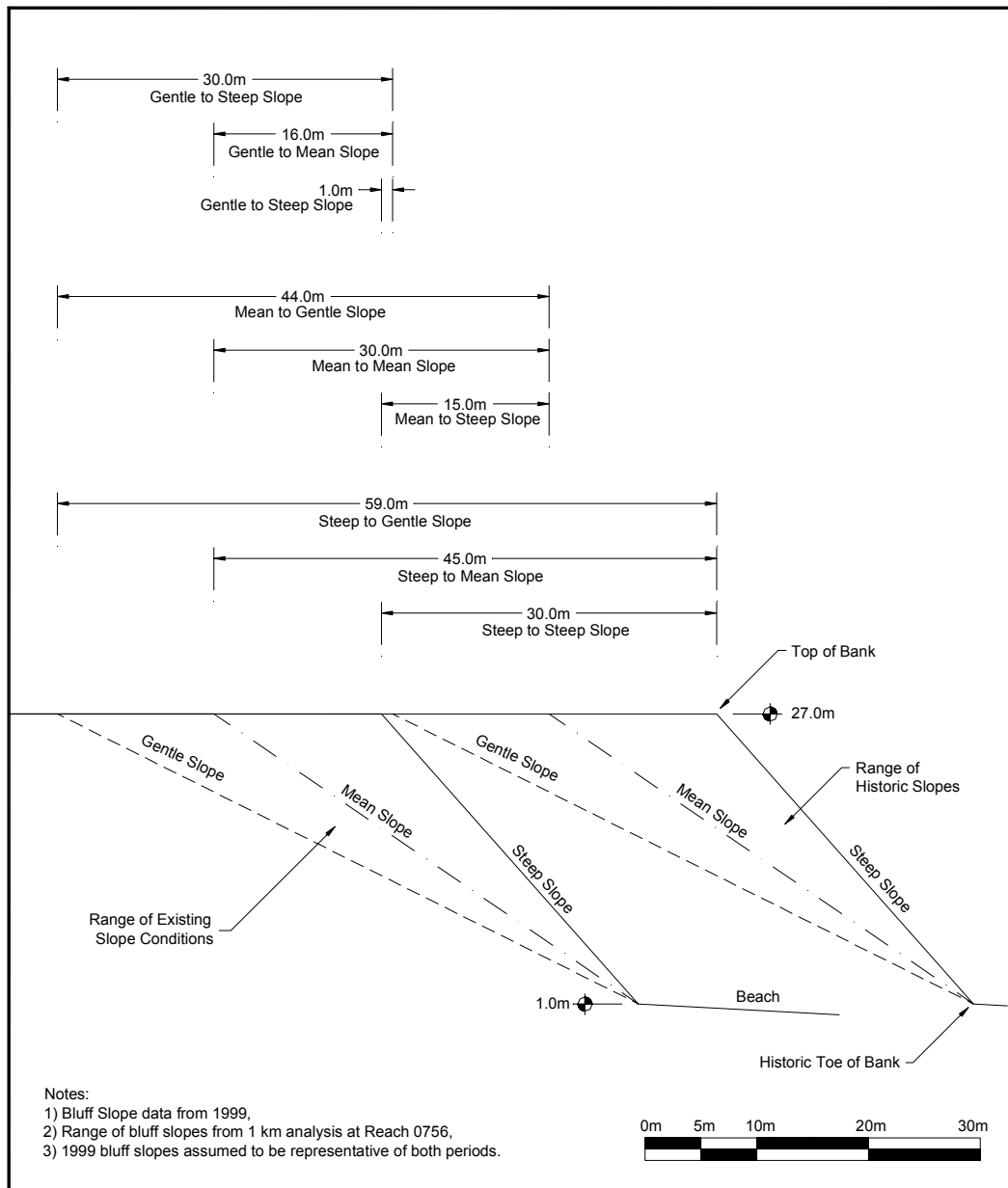
bluff slope was approximately 0.6 (V/H), however, there was significant variability in the slope conditions within the 1 km shoreline reaches and along the shore. The results in Figure 5.17 displayed many similar characteristics to the AER presented in Figure 5.15 for the nine detailed study reaches.

#### *5.2.1.4 Influence of Bluff Slope on Annualized Erosion Rates*

Based on the analysis of the 1999 bluff slope data, it seemed plausible that variability in bluff slope could explain the measured variability in the top of bank erosion rates between 1938 to 1989 for the 1 km shoreline reaches. Unfortunately, the historic shoreline data base only included top of bank lines. No historic toe of slope data was available to assess historic bluff slope influences on variability of AER.

In the absence of historic toe of bank data, it was assumed that the 1999 bluff slope was representative of the range of possible slope conditions (both in space and time) for the individual reaches. Based on this assumption, a methodology was developed to investigate the role of bluff slope on the variability of top of bank erosion measurements.

The assessment involved four steps: 1) preparing a 2D profile that was representative of the range of bluff slope conditions observed in the 1999 data; 2) shifting the bluff slope line 100 times the 1938 to 1989 annualized erosion rate (a 100 year shift was required due to the high degree of slope variability in the area), 3) measuring the combinations of top of bank erosion between the two sets of bluff slopes (i.e. representative of a historic to recent shoreline data set); and 4) comparison of variability (i.e. annualized standard deviation) in the erosion rates calculated from the hypothetical bluff slope data to the measured variability in the erosion rates between 1938 to 1989. The results for Reach 0756 are presented in Figure 5.18, with a 30 m lakeward shift ( $100 \times 0.3 \text{ m/yr}$ ).



**Figure 5.18 100 Year Shift of the 1999 Bluff Slope for Reach 0756 ( $100 \times 0.30 \text{ m/yr} = 30 \text{ m}$ )**

The range of 1999 bluff slope conditions used for the two time periods provided a total of nine comparisons of top of bank position for the hypothetical 100 year period (steep to steep, steep to mean, etc.). The horizontal distance for the nine slope pairs are representative of the longshore distribution of erosion transects within the reach. Due to the large variability in the bluff slope (i.e. from steep to gentle), the range of erosion from historic to recent top of bank ranged from 1.0 m for the gentle to steep slope pair, to 59 m for the steep to gentle pair.

The results for the nine hypothetical transects in Reach 0756 are summarized in Table 5.10. The annualized erosion rate ranges from 0.01 m/yr to 0.59 m/yr. This enormous range in AER is attributed entirely to variability in bluff slope, since the toe of bank is identical for all the historic and existing slopes. The annualized erosion rate based on the bluff shift data is identical to the AER from the 1938 to 1989 data, which is expected. However, the key finding is the annualized standard deviation for the hypothetical top of bank erosion rate data is almost identical to the measured annualized standard deviation (ASD) between the 1938 to 1989 top of bank lines (i.e. 0.18 and 0.16 m/yr respectively).

**Table 5.10**  
**Annualized Erosion Rates for Reach 0756 with Hypothetical Bluff Data**  
**9 Hypothetical Transect Measurements (refer to Figure 5.18)**

Transect	Hypothetical Historic to Recent Slope Conditions	Total Top of Bank Erosion (m)	Annualized Erosion Rate (m/yr)
1	gentle to steep	1	0.01
2	mean to steep	15	0.15
3	gentle to mean	16	0.16
4	gentle to steep	30	0.3
5	mean to mean	30	0.3
6	steep to steep	30	0.3
7	mean to gentle	44	0.44
8	steep to mean	45	0.45
9	steep to gentle	59	0.59

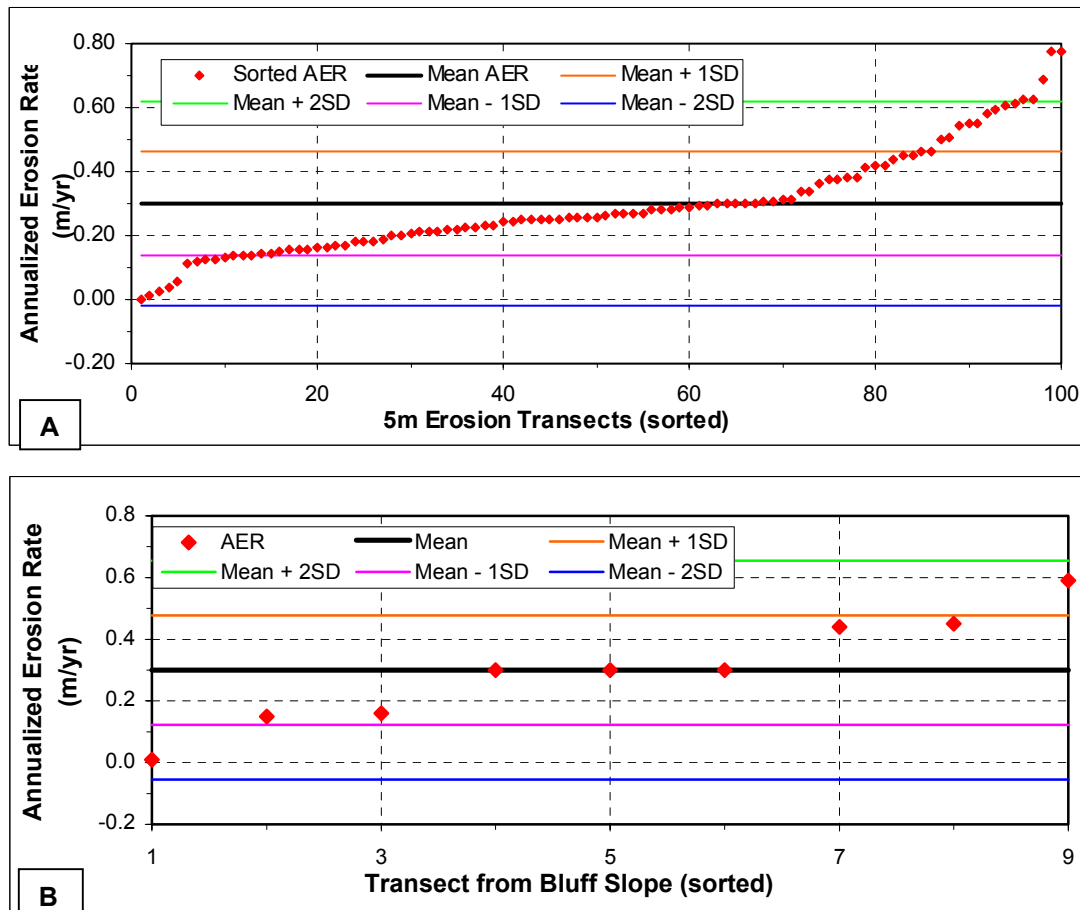
**Summary of Hypothetical Top of Bank Erosion Data Based on Shift**

Years between TOB	100
# of Transects	9
AER (100 years)	0.30
ASD (100 years)	0.18

**Measured 1938 to 1989 Top of Bank Erosion Data for Reach 0756**

Years between TOB	51
# of Transects	100
AER (1938 to 1989)	0.30
ASD (1938 to 1989)	0.16

The population distribution about the mean or AER for the actual 1938 to 1989 erosion rates are presented in Panel A of Figure 5.19. The sorted AER exhibit extreme variability about the mean rate of 0.3 m/yr. The distribution of the AER based on the bluff shift concept is plotted in Panel B. Although there are only nine data points in Panel B, the distribution of the points about the mean is remarkably similar to the actual field results presented in Panel A. The identical procedure was followed for Reach 0749 with very similar results (i.e. the mean erosion rate was identical and the ASD was very similar).



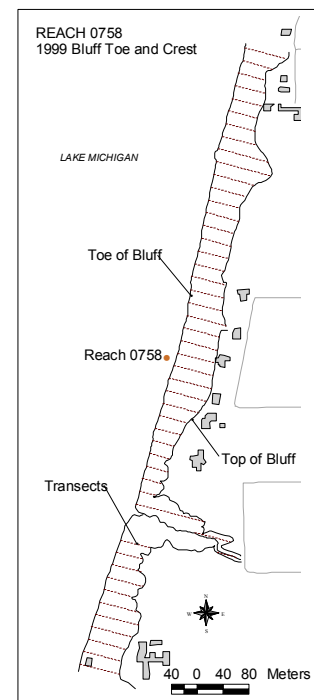
**Figure 5.19 Distribution of 1938 to 1989 Erosion Transects, Population Mean, and Standard Deviation for Reach 0756 (A) and Hypothetical Dataset (B)**

### 5.2.1.5 Gullies

Many of the cohesive reaches in the five prototype counties featured gullies or ravines of varying sizes and forms. An example of a large gully in Reach 0758 is recorded by the detailed toe and top of bank mapping in Figure 5.20. The formation of gullies along eroding bluff shorelines and the advance of the head and side walls is attributed to a set of complex and interrelated factors, including: local geology, surface and sub-surface

hydrology, land-use practices, rainfall intensity, flow velocity gradients in the gully stream and the erosion rate of the coastal bluffs.

Considering the evolution of the gullies is attributed to a variety of factors in addition to the erosion and retreat of the bluffs, prediction of future evolution was well beyond the capabilities of the COSMOS model and the existing suite of analysis tools in the FEPS. In addition, the economic damages associated with head and side wall retreat over a 50 year planning horizon was thought to be minimal when compared to the impacts of bluff erosion. Therefore, the future evolution of the gully features was not included in the analysis of the three LMPDS scenarios or the mapping of future shoreline position.



**Figure 5.20 Reach 0758 Gully**

## 5.2.2 *COSMOS Model Calibration*

The methods followed to create a COSMOS input menu, time series wave and lake level data and calibrate the erodibility coefficients are discussed.

### 5.2.2.1 *COSMOS Input Menus*

The GIS Profile Tool was used to extract 2D lake bed profiles from the 1999 SHOALS grids for southern Allegan County. An equilibrium profile was fitted to the profile geometry with a custom application in the FEPS UI. The bluff slope characteristics for each shoreline reach were extracted from the GIS database with the Shoretools and analyzed in the FEPS. The equilibrium profile and average bluff slope was combined in the COSMOS interface. Additional input parameters were adjusted as required (i.e. profile azimuth).

### 5.2.2.2 *ESWave Time Series Data*

A Baird wind wave hindcast was completed for Allegan County to provide historic hourly deep water wave data. The hindcast was centered on WIS Station 55. Linear refraction was used to transform the deep water wave climate to the reach specific depth and profile azimuth with ESWave. The ESWave module was also used to create a historic time series record of hindcasted waves, recorded lake levels and ice cover data. The historic

wave, water level and ice climate from 1973 to 1998 was assembled for each of the 26 shoreline reaches to calibrate the model.

In addition to the historic time series record assembled with ESWave, a 50 year time series file was created for each of the three LMPDS scenarios. In total, over 1.5 million hours of time series data was developed for each shoreline reach in Allegan County.

### 5.2.2.3 Calibration of Erodibility Coefficients

The three empirical erodibility coefficients used by the COSMOS model were described in Section 4.2.2.2. Prior to the model predictions for the LMPDS scenarios, each of the coefficients were calibrated based on 25 years of historic lake bed erosion and top of bank retreat based on the single value recession rates from 1938 to 1989. Table 5.11 presents the details of the calibration procedure, including the selected coefficients, 25 times the

**Table 5.11**  
**COSMOS Calibration Summary for Allegan County Cohesive Reaches**

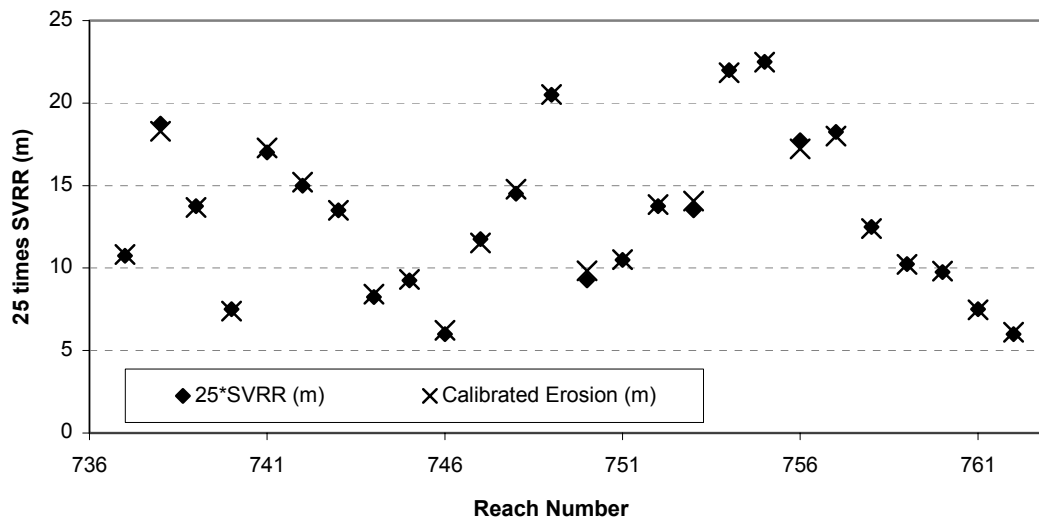
Reach	Azimuth (degrees from North)	COSMOS Menu				Calibration Details					
		Extracted Profile from GIS	Profile Type (A, B, or C)	Equilibrium Profile & Bluff Added to Menu	COSMOS Menu for Coastal Database	SVRR from Classification (m/yr)	SHEFAC Variable	DISFAC Variable	BLERODE Variable	25 Times the SVRR (m)	Calibrated Erosion Rate
737	279	Yes	B	Yes	0737-c99epB.men	0.43	6.00E-07	4.00E-09	5.50E-11	10.75	10.82
738	264	Yes	B	Yes	0738-c99epB.men	0.75	1.10E-06	1.00E-09	1.00E-10	18.75	18.29
739	267	Yes	B	Yes	0739-s99epB.men	0.55	8.00E-07	8.00E-10	7.50E-11	13.75	13.67
740	265	Yes	B	Yes	0740-s99epB.men	0.30	5.00E-07	8.00E-09	2.00E-11	7.50	7.38
741	264	Yes	B	Yes	0741-n99epB.men	0.68	1.20E-06	1.00E-09	6.90E-11	17.00	17.29
742	273	Yes	B	Yes	0742-c99epB.men	0.60	8.50E-07	8.00E-10	1.00E-10	15.00	15.21
743	284	Yes	A	Yes	0743-s99epA.men	0.54	8.00E-07	4.00E-10	1.10E-10	13.50	13.49
744	289	Yes	A	Yes	0744-c99epA.men	0.33	3.00E-07	4.00E-08	6.00E-11	8.25	8.42
745	279	Yes	B	Yes	0745-c99epB.men	0.37	5.00E-07	1.00E-08	4.50E-11	9.25	9.31
746	279	Yes	B	Yes	0746-s99epB.men	0.24	2.80E-07	7.00E-09	4.00E-11	6.00	6.22
747	279	Yes	B	Yes	0747-c99epB.men	0.47	8.00E-07	1.00E-08	4.70E-11	11.75	11.52
748	279	Yes	B	Yes	0748-n99epB.men	0.58	7.00E-07	4.00E-08	6.00E-11	14.50	14.78
749	276	Yes	B*	Yes	0749-n99epB.men	0.82	1.00E-06	5.00E-08	1.05E-10	20.50	20.52
750	277	Yes	B*	Yes	0750-c99epB.men	0.37	4.00E-07	1.50E-08	6.00E-11	9.25	9.83
751	275	Yes	B*	Yes	0751-c99epB-new.men	0.42	7.00E-07	1.00E-09	5.00E-11	10.50	10.52
752	275	Yes	B*	Yes	0752-c99epB.men	0.55	8.00E-07	8.00E-10	8.20E-11	13.75	13.85
753	273	Yes	B*	Yes	0753-s99epB.men	0.54	8.00E-07	4.00E-10	7.50E-11	13.50	14.06
754	279	Yes	B	Yes	0754-c99epB.men	0.88	1.10E-06	1.00E-08	1.50E-10	22.00	21.84
755	281	Yes	B	Yes	0755-n99epB.men	0.90	1.00E-06	6.00E-08	1.60E-10	22.50	22.48
756	283	Yes	B	Yes	0756-s99epB.men	0.71	1.10E-06	1.00E-09	1.00E-10	17.75	17.22
757	281	Yes	B	Yes	0757-c99epB1.men	0.73	1.10E-06	3.00E-08	1.10E-10	18.25	17.99
758	285	Yes	A	Yes	0758-c99epA.men	0.50	5.00E-07	5.00E-08	9.00E-11	12.50	12.39
759	287	Yes	A	Yes	0759-c99epA.men	0.41	5.00E-07	7.00E-09	2.80E-10	10.25	10.23
760	290	Yes	A	Yes	0760-n99epA.men	0.39	5.50E-07	1.50E-08	2.20E-10	9.75	9.81
761	290	Yes	A	Yes	0761-n99epA.men	0.30	4.00E-07	1.00E-08	8.00E-11	7.50	7.46
762	292	Yes	A	Yes	0762-n99epA.men	0.24	3.10E-07	1.00E-08	8.70E-11	6.00	6.10

#### PROFILE TYPE LEGEND

- A Till with Thick Sand Cover (>200 m3/m)
- B Till with Moderate Sand Cover (50 to 200 m3/m)
- B\* Cobble-Boulder with Moderate Sand Cover (50 to 200 m3/m)
- C Till with Thin Sand Cover (<50 m3/m)

SVRR and for comparison, the model prediction for the 25 year wave climate once calibrated.

The coefficients were adjusted accordingly until the historic lake bed erosion and top of bank retreat rates were reproduced with the calibration runs. After numerous iterations, the COSMOS model was able reproduce the historic rates of bluff erosion based on the SVRR. The results are summarized graphically in Figure 5.21 for the SVRR and the calibrated model erosion rates.



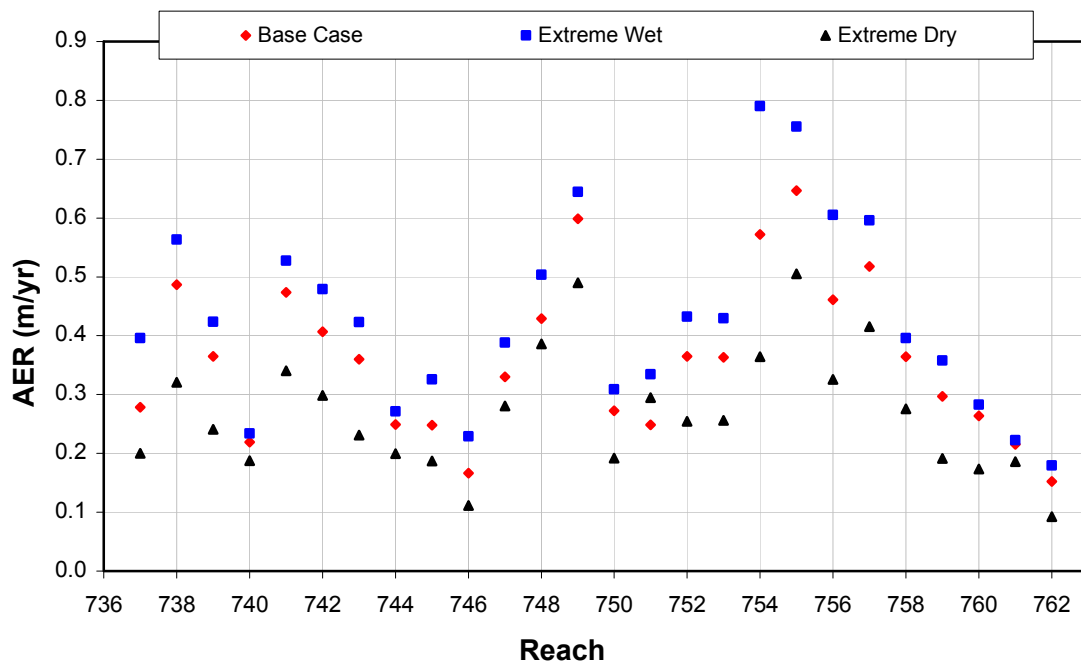
**Figure 5.21 Results of COSMOS Calibration Vs. Measured SVRR**

### 5.2.3 COSMOS Erosion Estimates for LMPDS Scenarios

The 50 year simulations were completed with COSMOS for all three of the LMPDS lake level scenarios for Reaches 0737 to 0762. The model records top of bank erosion at three periods in the time series, 20, 35 and 50 years. For purpose of comparison, the total amount of top of bank erosion was annualized after 50 years and is plotted in Figure 5.22. The following points summarize the findings:

1. Top of bank erosion was predicted for all three LMPDS scenarios;
2. In all cases, the amount of top of bank retreat was greatest for the extreme wet scenario. In most cases, the extreme dry scenario featured the lowest top of bank erosion rates;

3. The spread in the top of bank predictions between the scenarios in the individual reaches was variable along the shore and appeared to be related to nearshore slope. For example, reaches that featured a flat nearshore slope were more sensitive to the lake level changes between scenarios. Conversely, erosion rates for reaches that featured a steep nearshore were less sensitive to the different lake levels between the three scenarios;
4. The validity of the model estimates, especially the magnitude of erosion predicted for the three scenarios, is dependant on the accuracy of the SVRR, which are used to calibrate the erodibility coefficients. Due to the findings on the influence of transect spacing and bluff slope on AER, the results are preliminary until detailed top of bank retreat rates are calculated to verify the accuracy of the SVRR in the database.



**Figure 5.22 Comparison of COSMOS Erosion Estimates for the three LMPDS scenarios**

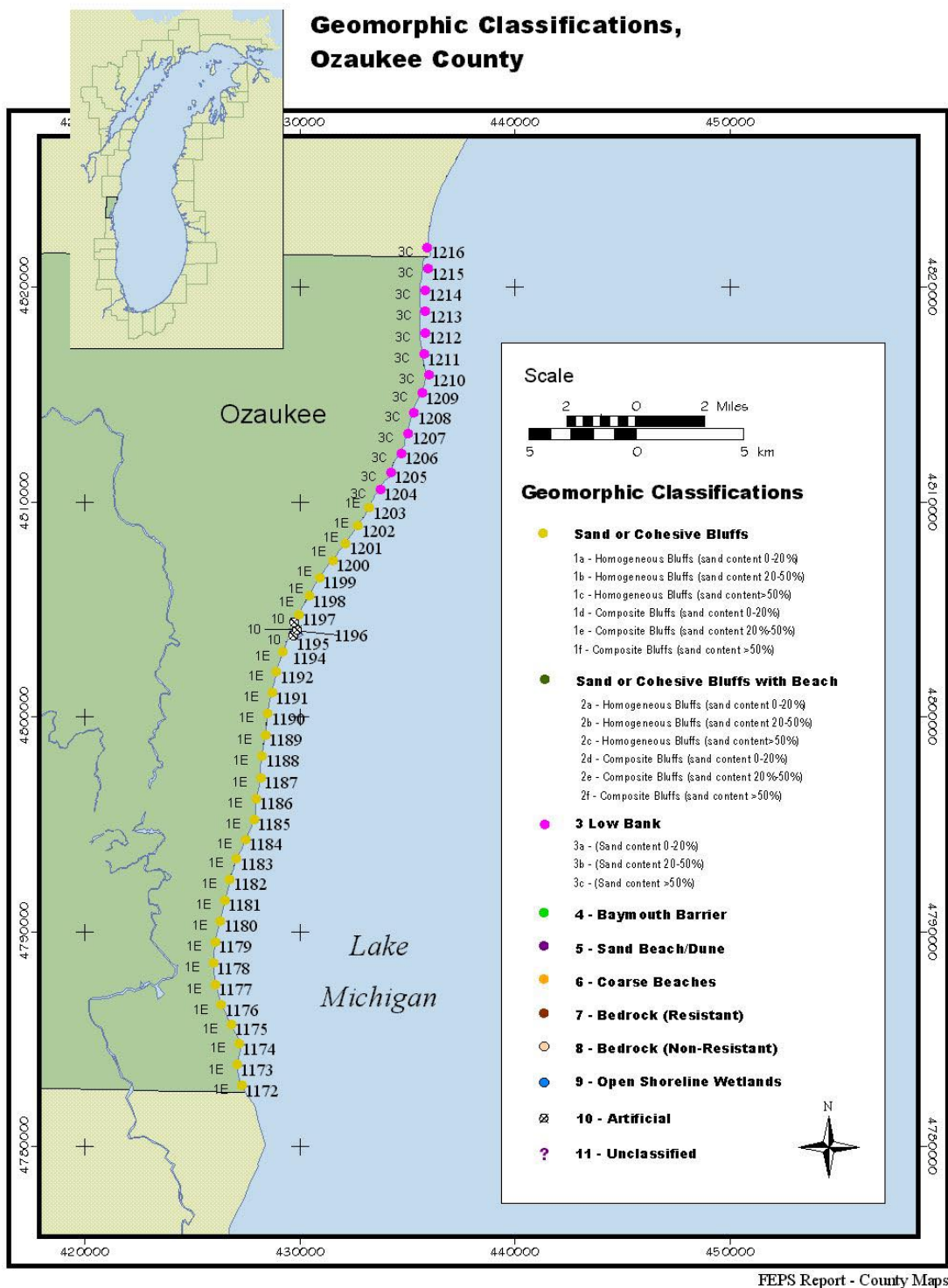
#### 5.2.4 Conclusions and Recommendations

The FEPS application to predict cohesive shore erosion in Allegan County was completed for 26 shoreline reaches. The investigation provided insight into several key physical processes and highlighted data needs to apply the FEPS. The following points summarize the major conclusions and provide recommendations:

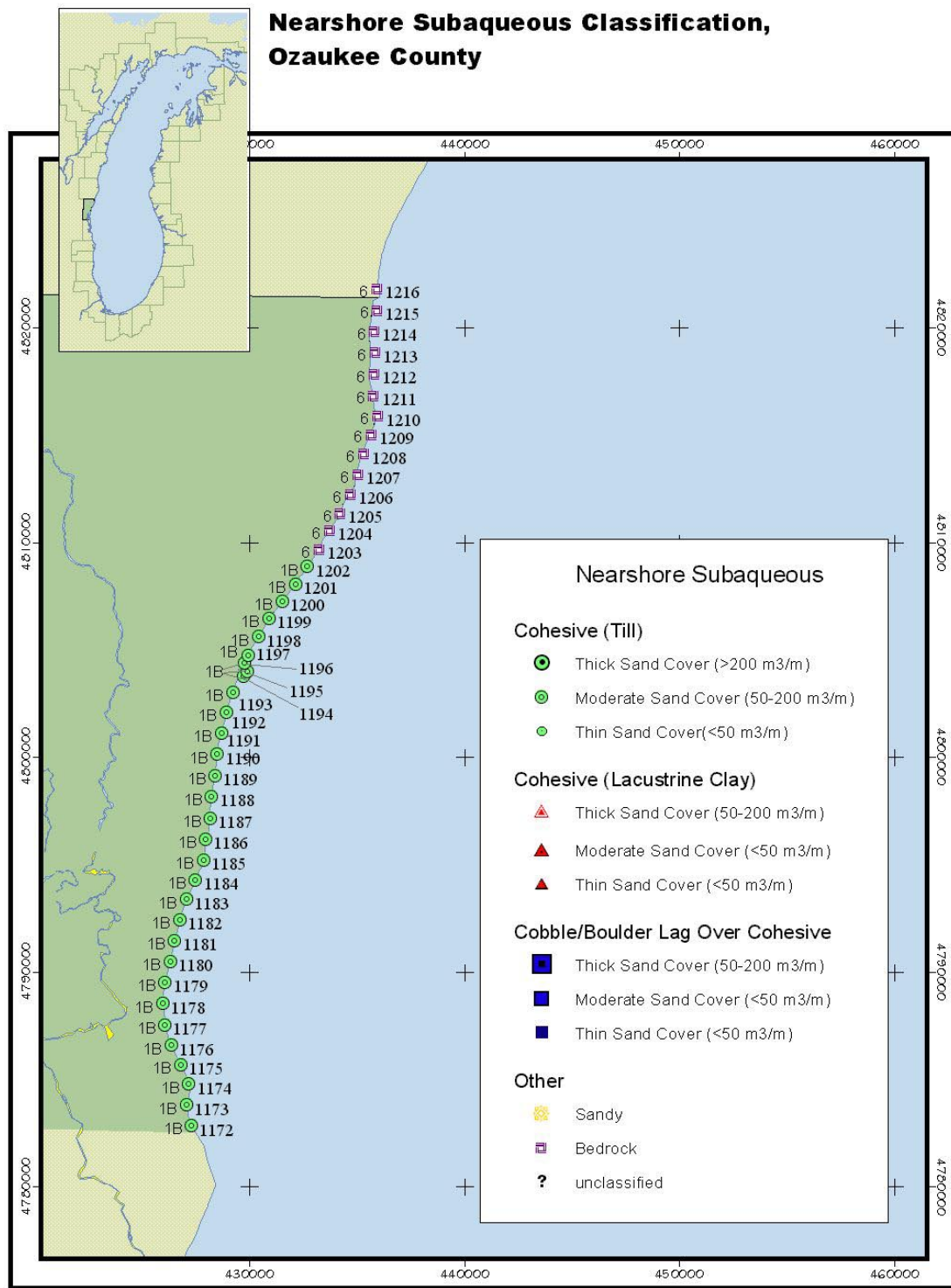
1. Due to the distance between the erosion transect measurements for the SVRR (i.e. approximately 200 m), the accuracy of the rates must be verified;
2. The SVRR for the high water period from 1973 to 1989 were 139% higher than the rates from 1938 to 1973, which featured a combination of low, average and high lake levels;
3. The detailed top of bank erosion rates from 1938 and 1989 exhibited extreme spatial variability within the 1 km shoreline reaches and along the entire southern half of Allegan County;
4. Bluff slope was found to be highly variable within the 1 km shore reaches and along the shore. The amount of variance in the annualized erosion rates measured from historic to recent top of bank positions in bluff slope was shown to be directly related to the variability in bluff slope;
5. Top of bank erosion was predicted for all three LMPDS scenarios over the 50 year simulation period. Erosion rates were higher for the extreme wet scenario and lower for the extreme dry scenario;
6. The preliminary modeling results suggest the spread in the top of bank retreat estimates between the three scenarios is related to lake bed slope. Reaches that feature a very flat slope are more sensitive to lake level fluctuations, while sites with a steep nearshore are less sensitive.

### **5.3 Ozaukee County – Cohesive Modeling 1172 to 1202**

Ozaukee County is located on the western shores of Lake Michigan, in the State of Wisconsin. Figure 5.23 provides a location map and the geomorphic classification for the shoreline. The southern two thirds of Ozaukee feature cohesive bluffs and are separated by Port Washington Harbor in the center of the county. North of Reach 1202, the shoreline switches from bluff to low bank. The portion of lake bed that corresponds to the cohesive bluff reaches has been classified as glacial till with moderate sand cover (Figure 5.24). Further north, bedrock forms the lake bed offshore of the low bank section. The cohesive Reaches from 1172 to 1202 were the focus of COSMOS erosion modeling with the FEPS. The coastal data, COSMOS erosion estimates and recommendations are presented below.



**Figure 5.23 Ozaukee County Geomorphic Classification**



FEPS Report - County Maps

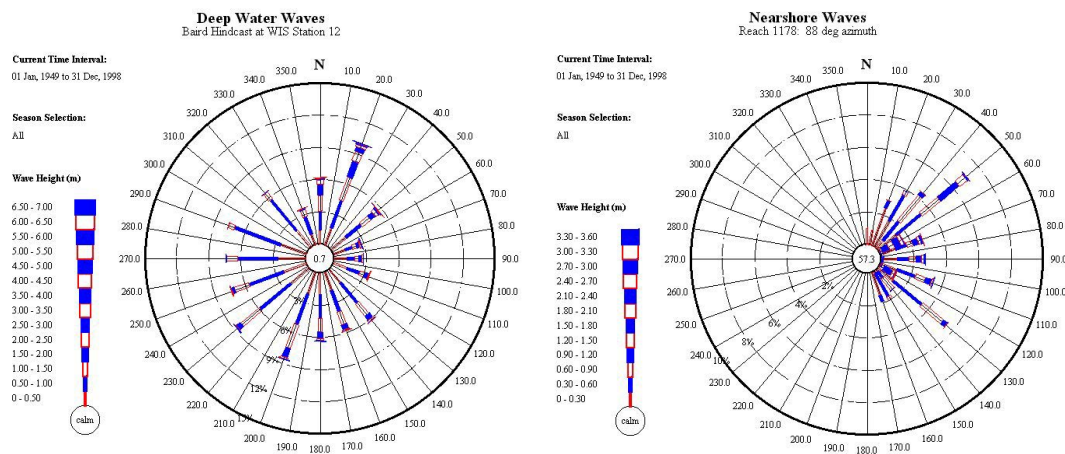
**Figure 5.24 Ozaukee County Subaqueous Classification (i.e. lake bed)**

### 5.3.1 Coastal Data and Analysis

The coastal data utilized by the FEPS for the analysis of cohesive shore erosion is discussed, including limitations of existing spatial data coverage.

#### 5.3.1.1 Waves and Lake Levels

A Baird wind wave hindcast was completed at WIS Station 12 to generate deep water time series wave data (i.e. wave height, period, and direction). The ESWave module was used to generate reach specific nearshore wave conditions. The offshore and nearshore wave data at Reach 1178 is presented in Figure 5.25. Historic lake levels were available from the Milwaukee gage (9087057).



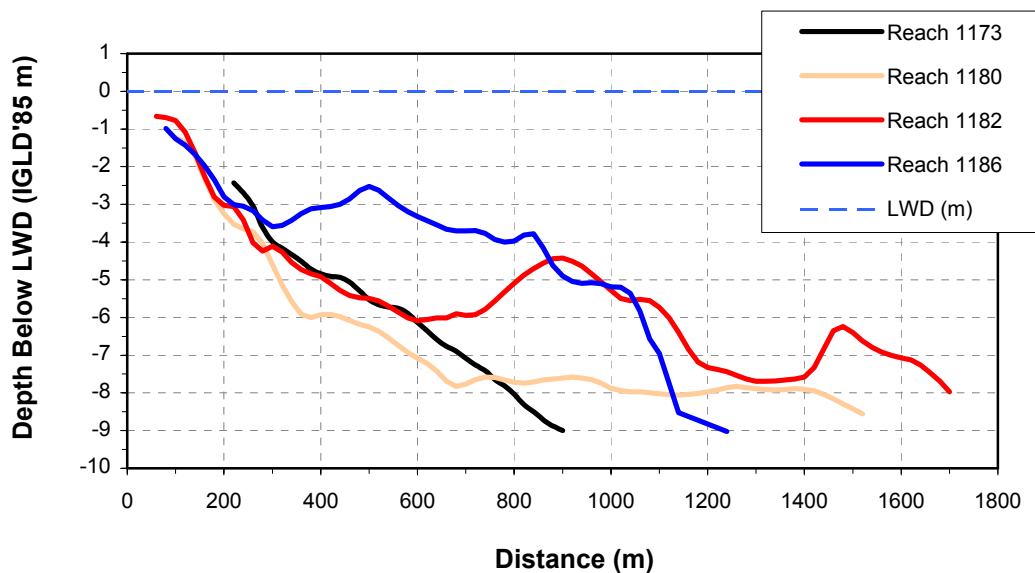
**Figure 5.25 Reach 1178 Offshore and Nearshore Wave Climate**

#### 5.3.1.2 Bathymetry and Topography

The 1999 SHOALS survey was unsuccessful in acquiring bathymetry data in Ozaukee County. Therefore, the historic 1913 survey by the USACE was used as the most recent regional bathymetric coverage. Copies of the historic field sheets were obtained from the National Archives in Washington, DC, digitized and projected into the UTM coordinate system.

A sample of four profiles from the cohesive reaches are presented in Figure 5.26. The profiles highlight the variable nature of the 1913 lake bed over a relatively small geographic area (13 km). The profile for Reach 1173 is relatively flat and features a 1:100 slope (V:H). The Reach 1180 profile has a similar form to 1173 out to the 7 m depth contour, then features a 800 m wide shelf at approximately the 8 m contour

elevation. The shelf may record the underlying bedrock that forms the nearshore lake bed further to the north. Reach 1182 follows the form of 1173 until the 6 m depth contour, then features two very large bar and trough features. The bar features may actually be glacial till that was armoured with boulders and cobbles (i.e. a localized occurrence of relatively high boulder and cobble content in the glacial till matrix). The final profile, Reach 1186, features a 500 m wide shelf at the 3 m depth contour that may also be protected by a boulder cobble lag deposit. After the shelf, the profile then dips steeply to the 9 m depth contour.



**Figure 5.26 1913 Lake Bed Profiles in Ozaukee County**

The absence of SHOALS data and the use of the 1913 bathymetry provided several modeling challenges and limitation for the FEPS, which are listed below:

1. Without recent bathymetry, it was not possible to complete a historic to recent 3D GIS comparison to investigate lake bed erosion patterns and rates. Consequently, it was not possible to evaluate the long term evolution of the unique and diverse profile conditions presented in Figure 5.26;
2. Without recent bathymetry data, there was no reliable starting point for the COSMOS lake bed erosion modeling in Ozaukee County;
3. The inshore limit of the 1913 survey varied from 1 to 2.5 m below LWD (due to surveying techniques). However, the historic mapping did include a waterline and bluff contours, which provided some indication of the nearshore slope in 1913. Nonetheless, this was a significant limitation of the 1913 data, since the nearshore

zone is a critical data area to accurately model the sensitivity of erosion to lake levels;

4. The COSMOS input profiles were a combination of bathymetry from 1913 and topography from 1999.

The 1999 topographic data provided detailed bluff toe and top of bank positional information for the COSMOS input menus. A methodology was developed to shift the 1999 bluff data lakeward 86 times the SVRR to mesh with the 1913 lake bed data. This was necessary to approximate the missing nearshore slope conditions for the 1913 bathymetry coverage.

#### *5.3.1.3 Single Value Recession Rates*

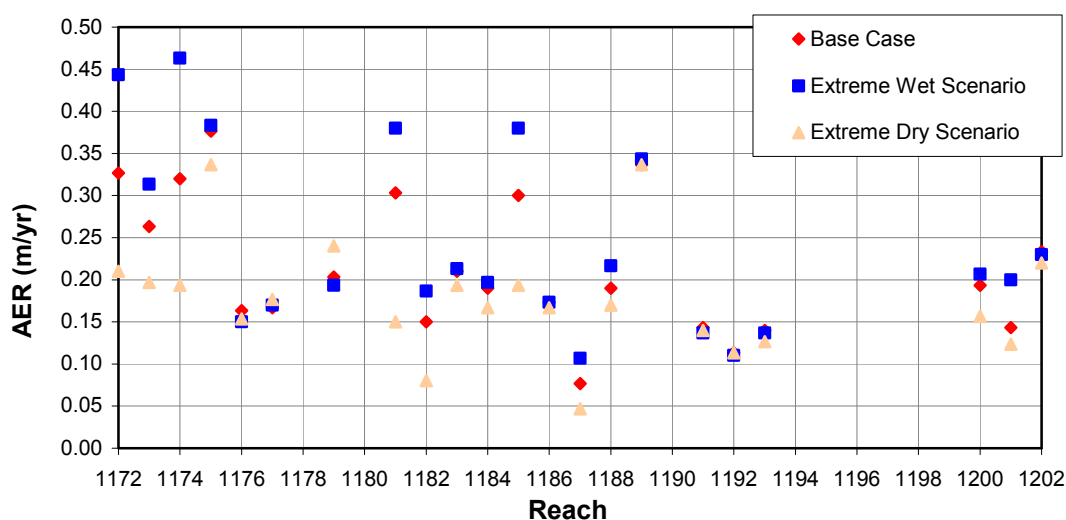
Historic erosion rate data for the 1 km shoreline reaches was available from numerous sources for Ozaukee County. The published recession rate data from various researches incorporates many temporal periods, different sampling densities and quite possibly just as many methods to calculate annualized erosion rates. A sample of the data was provided in Table 3.2 for Reach 1172, which exemplifies the difficulties in interpreting the information and incorporating the data in the FEPS. The database of published recession rates was reviewed on a reach by reach basis and the most appropriate long term erosion rate, that included a wide range of lake level conditions (i.e. highs and lows), was selected.

#### **5.3.2 COSMOS Erosion Estimates**

The COSMOS model was calibrated for the cohesive reaches in Ozaukee County. Refer to Section 5.2.2.3 for a detailed discussion on the methodology. Five reaches featured a SVRR below 0.1 m/yr, which is the cutoff for cohesive modeling, and were excluded from the calibration process (1178, 1180, 1190, 1198, and 1199). The estimates of future top of bank position in these reaches was calculated by multiplying the SVRR by 20, 35 and 50 years (i.e. the historic rates were just extrapolated into the future for all three scenarios). Consequently, the future estimates were identical for all three LMPDS scenarios. No modeling was completed for the reaches corresponding to the Port Washington Harbor, 1194 to 1197, since the shoreline was armoured with Level 1 protection (i.e. assumed stable and no erosion over the 50 year modeling horizon).

The 50 year annualized erosion rates predicted with the COSMOS model for the remaining reaches are presented in Figure 5.27. Due to the limitations of the bathymetry data and uncertainty about the accuracy of the SVRR, the results are preliminary. Regardless, there are some interesting trends in the results, which are summarized below:

1. As with the results for the cohesive modeling in Allegan County, the top of bluff is predicted to erode for all three LMPDS scenarios;
2. In most cases, the Extreme wet scenario featured the highest top of bank erosion rates and the Extreme dry scenario the lowest;
3. The spread in total top of bank retreat between the extreme wet and dry was highly variable, with the Extreme wet rates being approximately double for Reaches 1181, 1182, and 1185. Conversely, for Reaches 1176, 1177 and 1191 to 1193, the rates were almost identical for all three LMPDS scenarios (possibly due to lake bed slope).

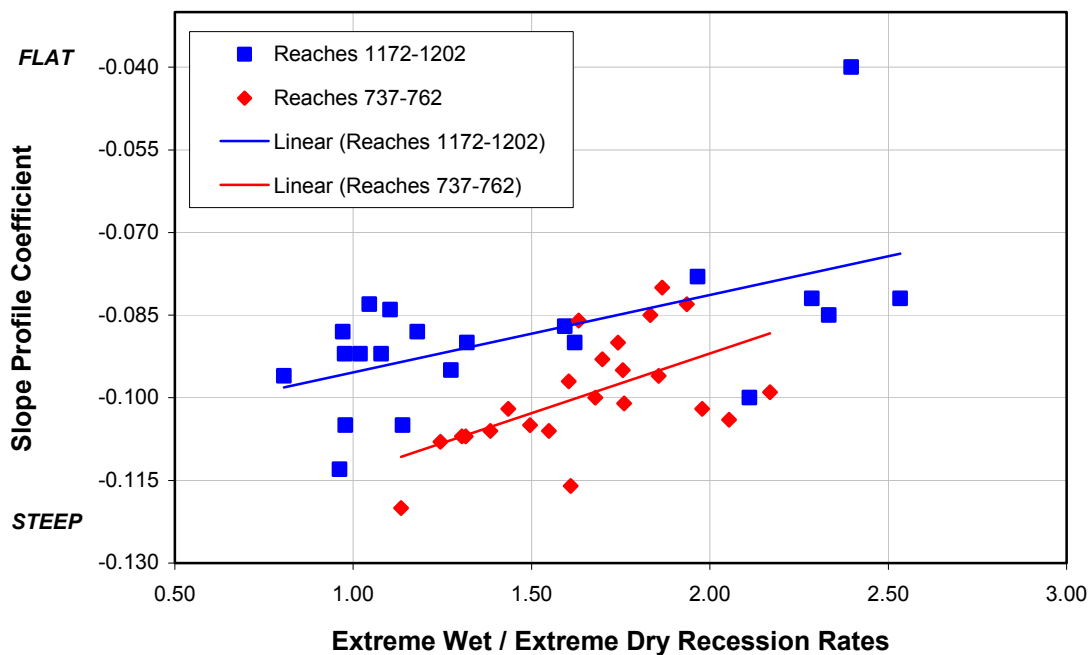


**Figure 5.27 AER for COSMOS 50 Year Erosion Predictions**

The influence of lake bed slope is investigated in Figure 5.28 for the COSMOS modeling results in Allegan and Ozaukee County. The X axis is a ratio of the Extreme wet versus Extreme dry annualized erosion rates and the corresponding Y axis is the lake bed slope coefficient used for the equilibrium profile. Although there is considerable scatter in both the Allegan and Ozaukee data, there does appear to be a quantifiable relationship between lake bed slope and the erosion sensitivity to lake level fluctuations.

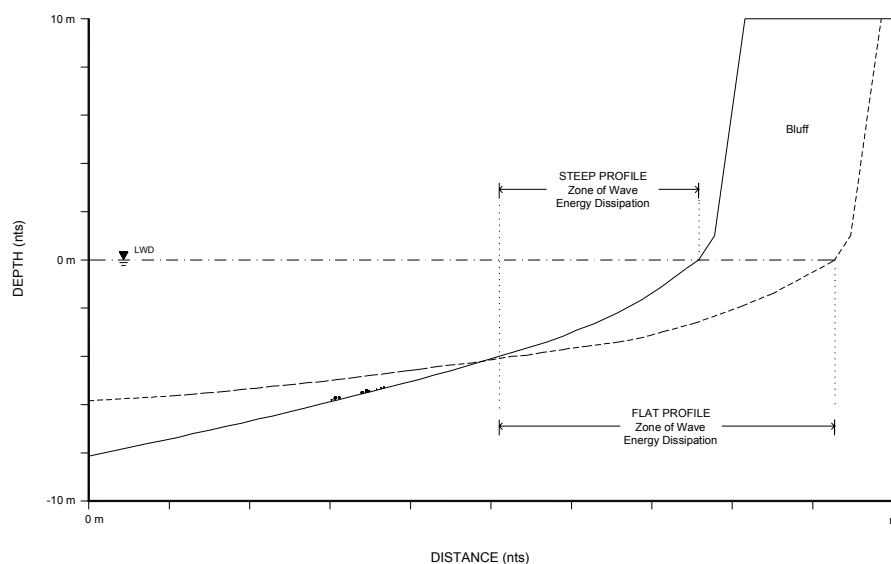
Figure 5.29 presents a conceptual sketch of the relationship between lake bed slope and the zone of wave energy dissipation, which is generally focused in the shallow nearshore zone from the 4 m depth contour to the waterline. In the sketch, the width of the nearshore zone from the 4 m contour to the waterline is almost double for the flat versus the steep nearshore profile.

For the flat profile in Figure 5.29, a significant increase in lake levels, such as the difference between the Extreme dry and Wet, will have a significant influence on the



**Figure 5.28 AER for COSMOS 50 Year Erosion Predictions**

amount of wave energy dissipation across the nearshore zone. For the extreme wet scenario, more wave energy reaches the beach and is capable of eroding the bluff toe. In the COSMOS model, this process translates into greater wave energy for the BLERODE coefficient (which relates wave energy to bluff erosion). Conversely, for the steep profile, the zone of wave energy dissipation in the nearshore is reduced and consequently a change in lake levels has less impact on the different magnitudes of wave energy dissipation between the extreme wet and dry scenarios.



**Figure 5.29 Influence of Lake Bed Slope on Wave Energy Dissipation**

### 5.3.3 *Conclusions and Recommendations*

Due to the absence of recent bathymetric data in Ozaukee County, the modeling results of cohesive shore erosion are preliminary. However, the FEPS analysis has provided a solid foundation for further modeling activities once recent bathymetric data is acquired. Also, the preliminary modeling results support the Allegan findings on the influence of lake bed slope on erosion sensitivity to lake level fluctuations.

## 5.4 Northern Ozaukee and Southern Sheboygan – Low Bank 1203 to 1234

The northern third of Ozaukee and the southern half of Sheboygan Counties feature a bedrock nearshore classification. A sample of the exposed bedrock at the waterline in Reach 1210 is presented in Figure 5.30. The bedrock nearshore is backed by low banks with sand content greater than fifty percent. Bank heights vary from 2 to 7 m. Field observations at Reaches 1209 to 1211 indicated the banks were sandy and heavily vegetated. The oblique aerial video also provided valuable insight into the actual field conditions for these reaches.



**Figure 5.30 Exposed Bedrock (1210)**

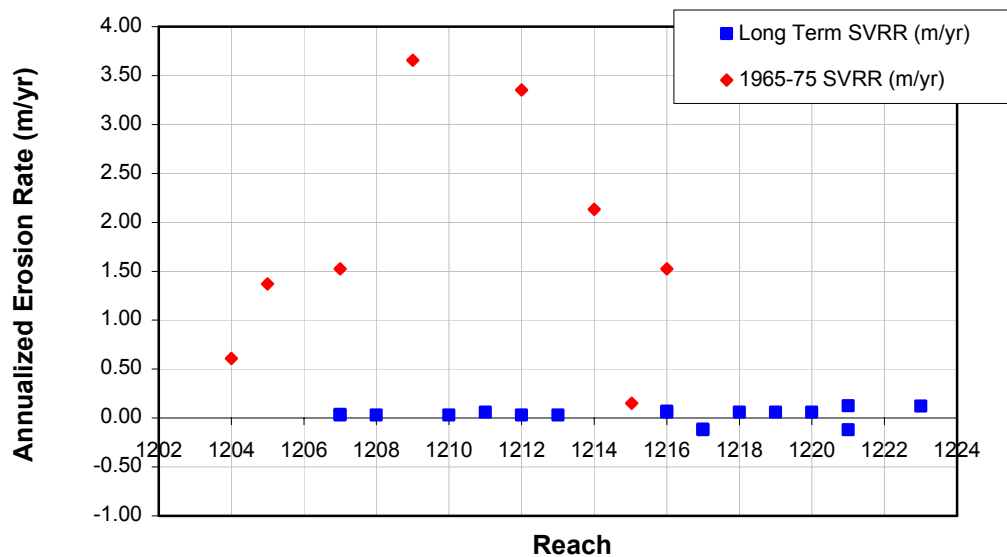
There are no harbors within the study limits of Reaches 1203 to 1234. Port Washington and Sheboygan are located approximately 6 km south and north of the reach boundaries (respectively). The fillet beaches associated with these two harbors are relatively small, especially when compared with the harbors on the east side of Lake Michigan. This observation, combined with the bedrock lake bed, indicate that sand and gravel sized sediment is not abundant in Ozaukee and Sheboygan Counties.

### 5.4.1 *Coastal Data and Analysis*

The coastal data utilized by the FEPS to analyze historic erosion processes is discussed, including the single value recession rates, lake bed bathymetry, and inputs to the sediment budget.

#### 5.4.1.1 Single Value Recession Rates

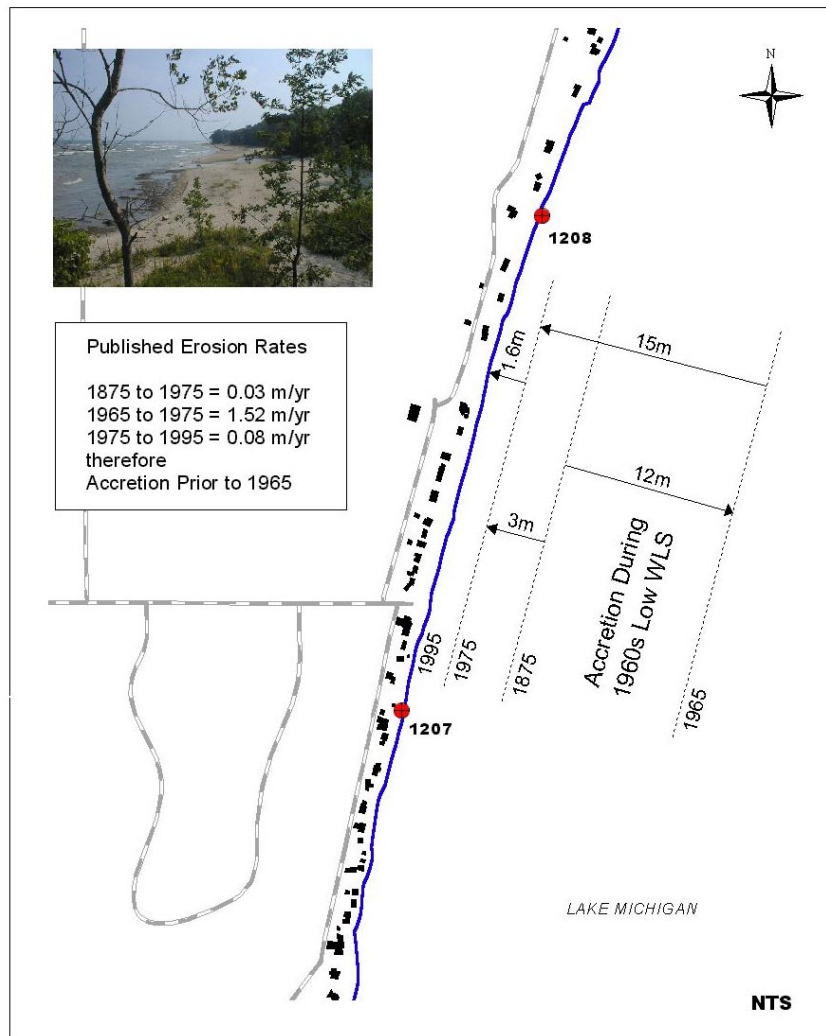
All of the published erosion rate data was examined for the study reaches in addition to the SVRR that were selected for the shoreline classification. The analysis revealed some interesting trends. The SVRR based on long term data (i.e. in excess of 100 years) are presented in Figure 5.31 for Reaches 1204 to 1223 and indicate that the shoreline has been generally stable in the long term. The rates of erosion and accretion were generally less than 0.1 m/yr. For comparison, the results for a 10 year period from 1965 to 1975 are also presented in Figure 5.31. After a period of record low levels in the mid 1960s, the Lake Michigan water levels increased by approximately 1.7 m over a 10 year period (see Figure 5.2). The erosion response to the lake level increase resulted in AER between 0.5 to 3.5 m/yr.



**Figure 5.31 Long and Short Term Annualized Erosion Rates**

If the lake bed is indeed bedrock, then the long term bank erosion rates must be zero or close to zero, as the long term SVRR suggest. However, as the comparison of the AER from these two temporal periods clearly highlights, short term cross-shore lake level induced erosion can occur during periods of rising lake levels. If the long term AER is correct, the shore must be able to recover from erosion during average and low lake level periods.

Figure 5.32 presents three published AER for Reach 1207 which document graphically the recovery or accretion of the sandy shoreline during the low lake levels in the 1960s. The topographic mapping from 1999 is assumed to represent the 1995 shore conditions for the purpose of the comparison. From 1875 to 1975, the AER of 0.03 m/yr results in

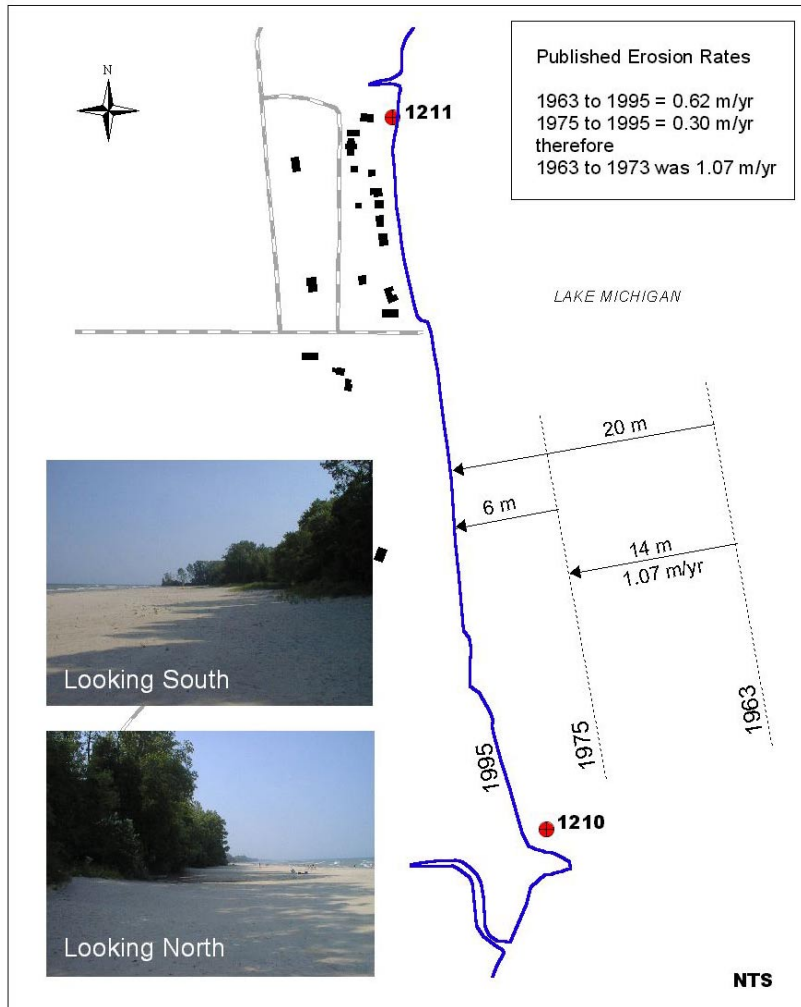


**Figure 5.32 Shoreline Accretion Documented by Published AER (1207)**

3 m of shore erosion. However, this long term retreat estimate is at odds with the 1965 to 1975 AER of 1.52 m/yr, which documents approximately 15 m of erosion. However, if shoreline accretion of 12 m occurred during the record low levels in the mid 1960s, as indicated on Figure 5.32, the published erosion rates record cross-shore profile recovery. From 1975 to 1995, a low AER returned to Reach 1207 (0.08 m/yr).

The influence of rising lake levels is captured in the published AER for Reach 1210 in Figure 5.33. Two site photographs in Figure 5.33 present the shore and bank conditions looking north and south in July 2000, during low lake level conditions. The temporal period for the two published AER both end in 1995. This allows the total erosion distance from 1963 to 1975 to be isolated (i.e. 14 m). Consequently, the AER during the

rising lake level period was 1.07 m/yr, which is more than three times greater than the 1975 to 1995 rate of 0.3 m/yr for a high lake level period.



**Figure 5.33 Shoreline Accretion Documented by Published AER (1207)**

Table 5.12 summarizes the AER for Reach 1216, which document annualized rates of change ranging from 0.06 m to 1.52 m of erosion per year. The wide range of AER is attributed to the following:

1. The AER were only based on only one transect measurement for the 1 km reach, which is not sufficient to establish a useful representative erosion rate;
2. The temporal scales vary from 10 to 142 years. This range encompasses a wide range of lake level conditions, which have been shown to result in erosion and accretion cycles for this stretch of shoreline;

3. The results were published by four agencies, all of whom could have been using different methods, data quality standards, and shoreline change reference features (i.e. waterline, edge of active dune vegetation, and top of bank). Collectively, these potential differences in techniques to calculate AER make the comparison of data from different researchers difficult. None of the results in Table 5.12 are of appropriate quality for the FEPS modeling.

**Table 5.12**  
**Sample of Annualized Erosion Rates for Reach 1216 (Sheboygan Ozaukee County Line)**

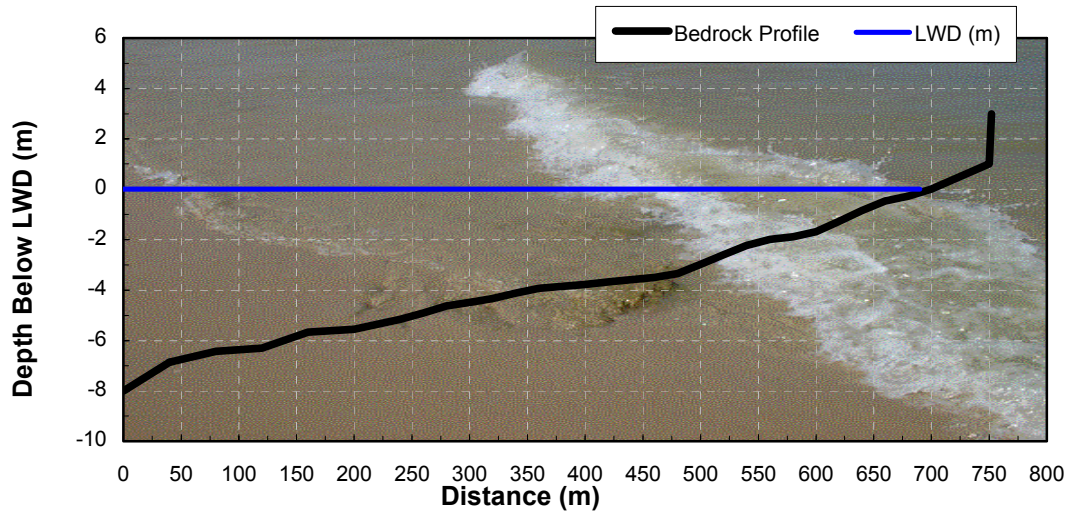
Reach	Annualized Erosion Rate (m/yr)	# of Samples	Years of Record	Confidence (1 is high)	Agency
1216	0.07	1	142	3	1834-1976 Buckler (1981); Buckler and Winters (1983)
1216	0.06	1	100	4	1875-1975 APPROX Wisconsin CZM (Acomb et al., 1977)
1216	1.25	1	32	2	1963-1995 SEWRPC (1997)
1216	1.22	1	25	2	1970-1995 SEWRPC (1997)
1216	0.91	1	20	2	1975-1995 SEWRPC (1997)
1216	1.52	1	10	4	1965-1975 APPROX Wisconsin CZM (Acomb et al., 1977)

#### 5.4.1.2 Bathymetry

The SHOALS system was not successful in collecting data in Ozaukee and Sheboygan Counties. Consequently, the 1913 USACE survey was the only regional dataset available and was utilized to generate 3D lake bed grids and extract 2D profile for the COSMOS model.

A 3D bathymetry comparison was not possible to confirm the bedrock nearshore classification was correct and confirm that the lake bed has been stable since 1913. It is also not possible to answer important questions about the zone of active sediment movement and the stability of the nearshore zone. These unanswered questions are further confounded when the uncertainties associated with the historic erosion rates for Reaches 1203 to 1234 are considered.

An example of a 2D profile extracted from the 1913 bathymetry grid for Reach 1210 is presented in Figure 5.34. The separation between points in the 1913 survey is approximately 100 m and smaller bar features are often not recorded at this resolution. However, regardless of this limitation, the data does suggest a very flat profile, with a nearshore slope of ~1:90 (V:H), which is characteristic of a bedrock nearshore substrate.



**Figure 5.34 1913 Bedrock Lake Bed Profile**

#### 5.4.1.3 COSMOS Longshore Sediment Transport Modeling

Longshore sediment transport (LST) modeling was completed with the COSMOS model and the 1913 bathymetry profiles. From Reach 1203 to 1223 the lake bed was classified as bedrock, which was assumed to extend up to the LWD (0.0 m). Therefore, the LST estimates were shut down for the lake bed (i.e. assumed zero potential for LST). There may actually be bars and isolated deposits of sand in the nearshore above the bedrock lake bed, however, without the detailed SHOALS data, it was not possible to investigate this observation. Inshore of the 0.0 m contour, the profile was sandy in the model input menu and transport was possible in the swash zone. From 1224 to 1234, the entire input profile in COSMOS was sandy.

For the reaches with a bedrock lake bed, the COSMOS estimates of LST were limited to the swash zone and were consequently very low. The net LST rates ranged from less than 50 m<sup>3</sup>/yr to 900 m<sup>3</sup>/yr (Table 5.13). Due to the sinuous nature of the shoreline orientation from 1203 to 1223, the direction of net transport varied from north to south.

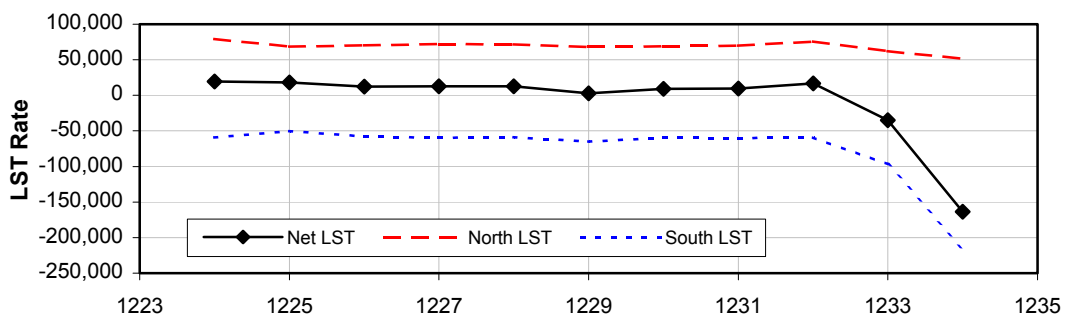
From Reach 1224 to 1234, the entire 2D profile in the COSMOS input menu was sandy. Consequently, the magnitude of the gross and net transport per reach increased significantly over the bedrock lake bed section. The net direction of LST is to the north and ranges from 3,000 to over 30,000 m<sup>3</sup>/yr (Table 5.13). The general shoreline orientation changes abruptly from Reach 1233 to 1234, and consequently the net direction of longshore sediment transport changes to southward. It is questionable whether the potential LST rates in Table 5.13 are actually achieved, especially for Reach 1234. The supply area for new littoral drift material is limited to the eroding cohesive bluffs over a

**Table 5.13**  
**Sediment transport Rates for Reaches 1203 to 1234 (Northern Ozaukee and Southern Sheboygan)**

Reach	Lake Bed	Base Case Waves and Lake Levels				Bluff Inputs to Sediment Budget			
		LST to the North (m <sup>3</sup> /yr)	LST to the South (m <sup>3</sup> /yr)	Net LST (m <sup>3</sup> /yr)	Direction of Net LST	Avg. Bluff Height (m)	SVRR (m/yr)	% Sand in Bluff	Annual Bluff Inputs (m <sup>3</sup> /yr)
1203	Bedrock	1,393	-490	902	N	25.00	0.23	75%	4313
1204	Bedrock	915	-308	607	N	5.71	0.18	75%	771
1205	Bedrock	1,025	-351	675	N	5.00	0.14	75%	525
1206	Bedrock	1,170	-406	764	N	2.12	0.18	75%	286
1207	Bedrock	1,042	-827	216	N	3.00	0.24	75%	540
1208	Bedrock	992	-394	598	N	2.64	0.15	75%	297
1209	Bedrock	676	-268	408	N	2.00	0.32	75%	480
1210	Bedrock	672	-832	-160	S	3.09	0.62	75%	1437
1211	Bedrock	578	-815	-237	S	2.54	0.26	75%	495
1212	Bedrock	758	-939	-181	S	2.98	0.15	75%	335
1213	Bedrock	467	-559	-92	S	2.02	0.52	75%	788
1214	Bedrock	527	-480	47	N	2.45	0.26	75%	478
1215	Bedrock	521	-476	45	N	2.59	0.52	75%	1010
1216	Bedrock	538	-947	-409	S	2.21	1.25	75%	2072
1217	Bedrock	326	-268	57	N	3.49	-0.113	75%	-296
1218	Bedrock	566	-246	320	N	3.33	0.06	75%	152
1219	Bedrock	378	-175	203	N	3.00	0.06	75%	137
1220	Bedrock	488	-155	333	N	3.50	0.06	75%	160
1221	Bedrock	527	-182	344	N	4.00	0.125	75%	375
1222	Bedrock	501	-174	327	N	4.34	0.31	75%	1009
1223	Bedrock	512	-170	342	N	3.06	0.12	75%	280
1224	Sandy	79,103	-59,409	19,694	N	3.00	0.22	75%	495
1225	Sandy	68,590	-50,316	18,273	N	3.00	0.31	75%	698
1226	Sandy	70,372	-57,894	12,478	N	3.00	0.31	75%	698
1227	Sandy	72,295	-59,490	12,806	N	4.32	0.31	75%	1004
1228	Sandy	71,704	-58,859	12,845	N	7.00	-0.015	75%	-79
1229	Sandy	68,037	-65,284	2,754	N	7.34	0.31	75%	1707
1230	Sandy	68,813	-59,621	9,192	N	4.10	0.31	75%	953
1231	Sandy	69,710	-60,236	9,474	N	3.00	0.31	75%	698
1232	Sandy	75,908	-59,103	16,805	N	3.00	-0.0183	75%	-41
1233	Sandy	62,093	-96,898	-34,805	S	4.02	0.31	75%	935
1234	Sandy	51,438	-215,253	-163,816	S	5.00	0.31	75%	1163
<b>Total</b>									23873

Note: 1) Bluff Inputs per reach = 1000m\*bluff height\*SVRR\*sand%

small 5 km stretch between 1234 and the Sheboygan harbor, which is a littoral barrier. Figure 5.35 presents the LST results graphically for Reaches 1223 to 1234. The northern and southerly components of LST are plotted, along with the net rates per reach. Clearly the net rates are very low when compared to the gross transport and very close to zero.



**Figure 5.35 LST Rates for Reaches 1224 to 1234**

#### *5.4.1.4 Inputs from Bluff Erosion*

Since Reaches 1203 and 1234 are bounded by two large harbors, the primary input to the regional sediment budget is sediment from bluff and lake bed erosion. Table 5.13 also lists the average bluff height per reach and the most appropriate SVRR based on a review of all available data. Due to the low average bluff height and relatively low AER, the total sediment input from bank erosion is only 24,000 m<sup>3</sup>/yr for the 32 km segment of shoreline.

The results of the sediment budget calculations for bluff inputs support the observation that sediment availability is minimal and nearshore sinks are likely small.

#### *5.4.2 Summary of Analysis*

Collectively, the analysis of the existing information in the coastal database, the sediment budget calculations completed with the FEPS for Reaches 1203 to 1234, and the field observations suggest that in the long term, the shoreline is stable. The long term AER are very low and changes in shoreline position due to gradients in longshore sediment transport rates are also low or non-existent. Consequently, a long term shoreline change rate of 0.0 m/yr was assumed for the mapping of future shoreline position (discussed in Section 6.0 of the report).

Significant short term cross-shore lake level related erosion can occur and result in significant retreat of the beaches / low banks (i.e. in excess of 3 m/yr). However, when average and low lake levels return, the shore can recover from these periods of high erosion rates. Further study of the cross-shore lake level effect is required to quantify the magnitude of profile adjustment and develop a defensible approach to model the lake level influences of the LMPDS scenarios.

The spatial extent of the bedrock lake bed must be documented in the nearshore zone and the presence / absence of nearshore sand bars must be confirmed to refine the model estimates of LST. The annual sediment inputs from bluff erosion support the small potential LST rates, especially for the bedrock lake bed reaches.

#### *5.4.3 Recommendations for Reach 1203 to 1234*

Based on the FEPS application for Reaches 1203 to 1234 and the summary analysis in the previous section, the following recommendations are provided for further data collection and studies:

1. The presence and spatial extent of the bedrock lake bed must be confirmed with field observations;

2. A recent bathymetric survey is required to complete a historic to recent 3D comparison and provide input to the COSMOS model;
3. Additional field observations are required to confirm the geomorphic characteristics of the low bank classification (i.e. 100% sand versus cohesive sediments);
4. The low bank shore classification is ambiguous and should be replaced with sandy low banks and cohesive low banks;
5. Accurate historic top of bank mapping is required to calculate reach specific AER for the low banks from Reaches 1203 to 1234.

## **5.5 Northern Sheboygan and Manitowoc – Cohesive Modeling 1235 to 1318**

The Lake Michigan shoreline, from Reach 1235 to 1318, was identified as a cohesive shoreline in the three tiered classification. The reaches include the northern half of Sheboygan and Manitowoc County. Figure 5.36 provides a view of the eroding cohesive bluffs at Two Creeks. Three large harbors, Sheboygan, Manitowoc and Two Rivers are located in the two counties.

The one exception to the cohesive shore classification is a sandy beach and nearshore designation for Reaches 1297 to 1309, which form the approximate boundaries of the Point Beach State Forest (Refer to Section 5.6) in Manitowoc County. The coastal data, FEPS erosion modeling, and recommendations are presented in the following sections.



**Figure 5.36 Two Creeks, April 28, 1999**

### **5.5.1 Coastal Data and Analysis**

The coastal data utilized by the FEPS to model cohesive shore erosion is outlined, including the shoreline classification, the single value recession rates, a historic profile comparison and the bathymetry / topography data.

### 5.5.1.1 Shoreline Classification

The geomorphic classification for Reaches 1216 to 1317 is summarized in Figures 5.37a and b for Sheboygan and Manitowoc Counties. The sandy beach / dune classification for Point Beach State Forest is noted on Figure 5.37b. The nearshore subaqueous classification for Sheboygan and Manitowoc is presented in the county maps in Figures 5.38a and b. The cobble boulder lag designation dominates the northern half of Sheboygan and the southern half of Manitowoc County. Between the harbors at Two Rivers and Manitowoc, the lake bed is designated as glacial till.

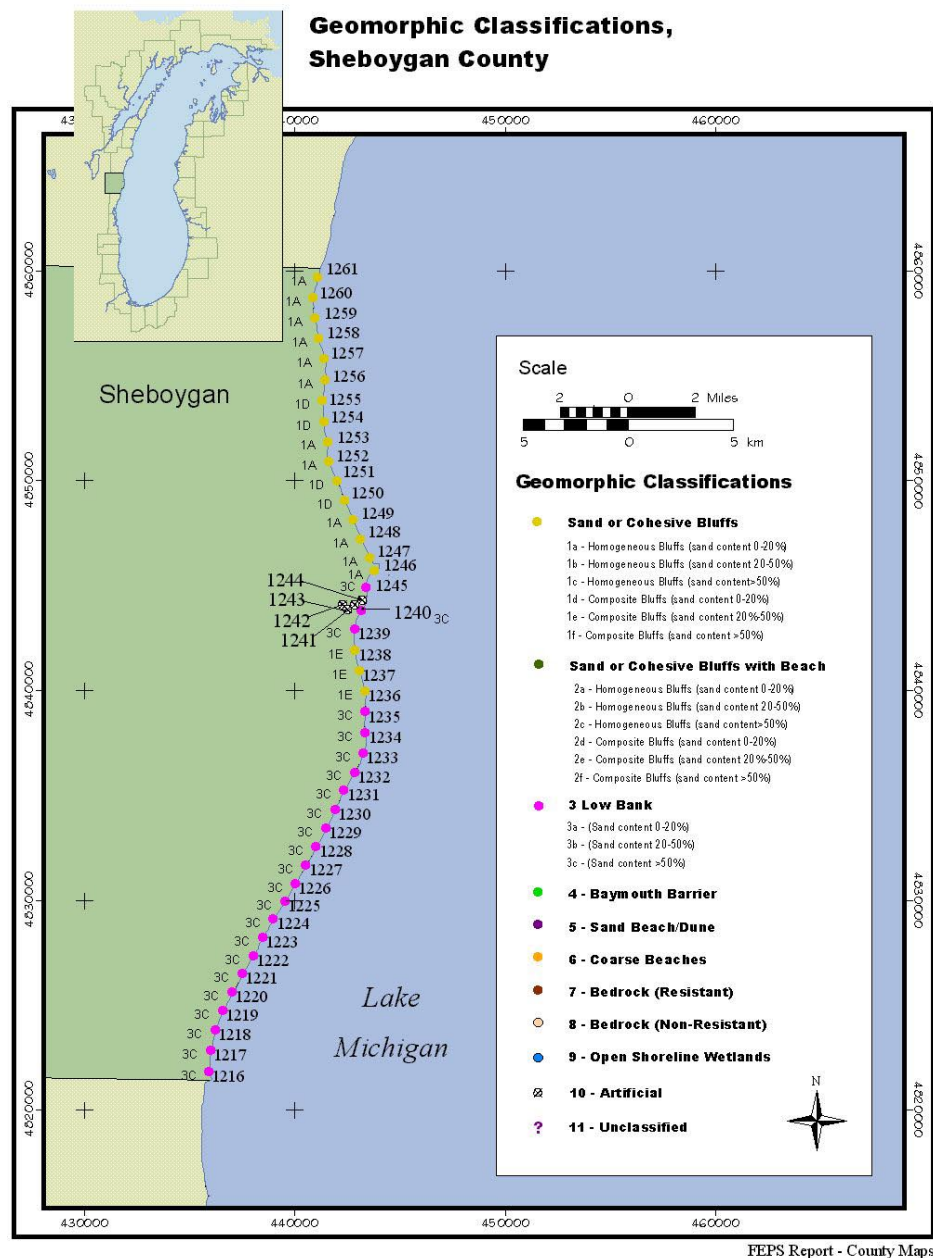
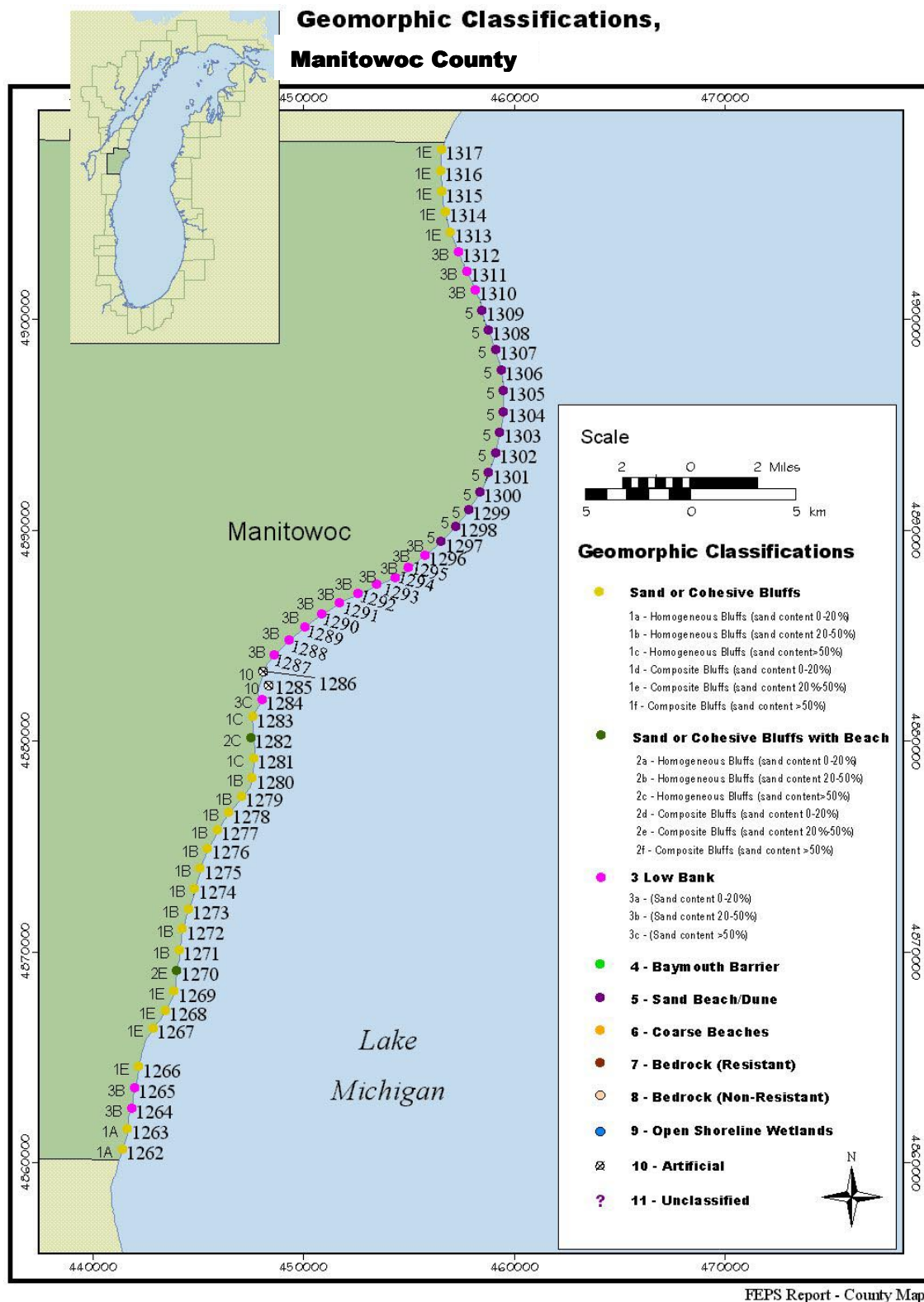
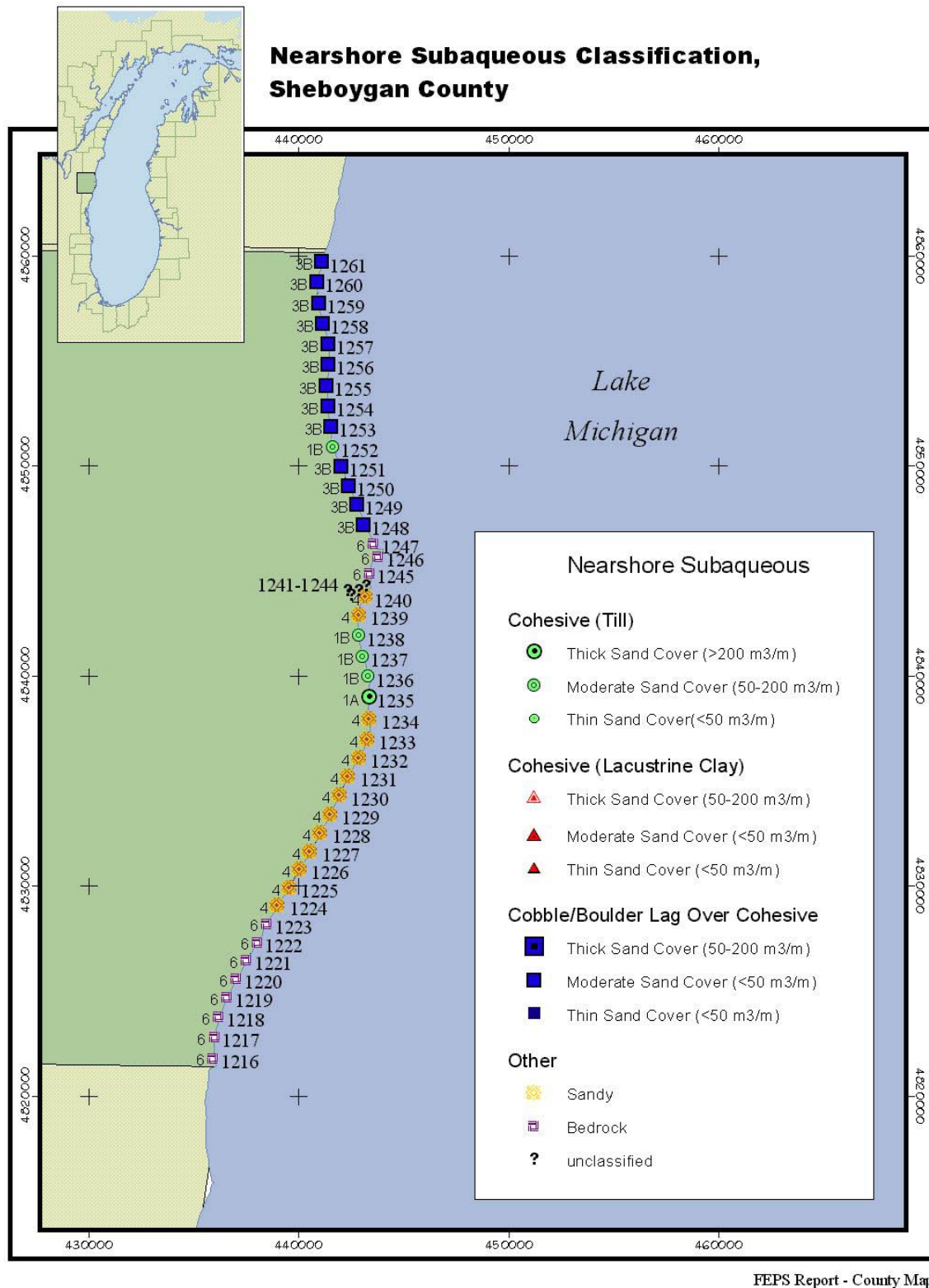
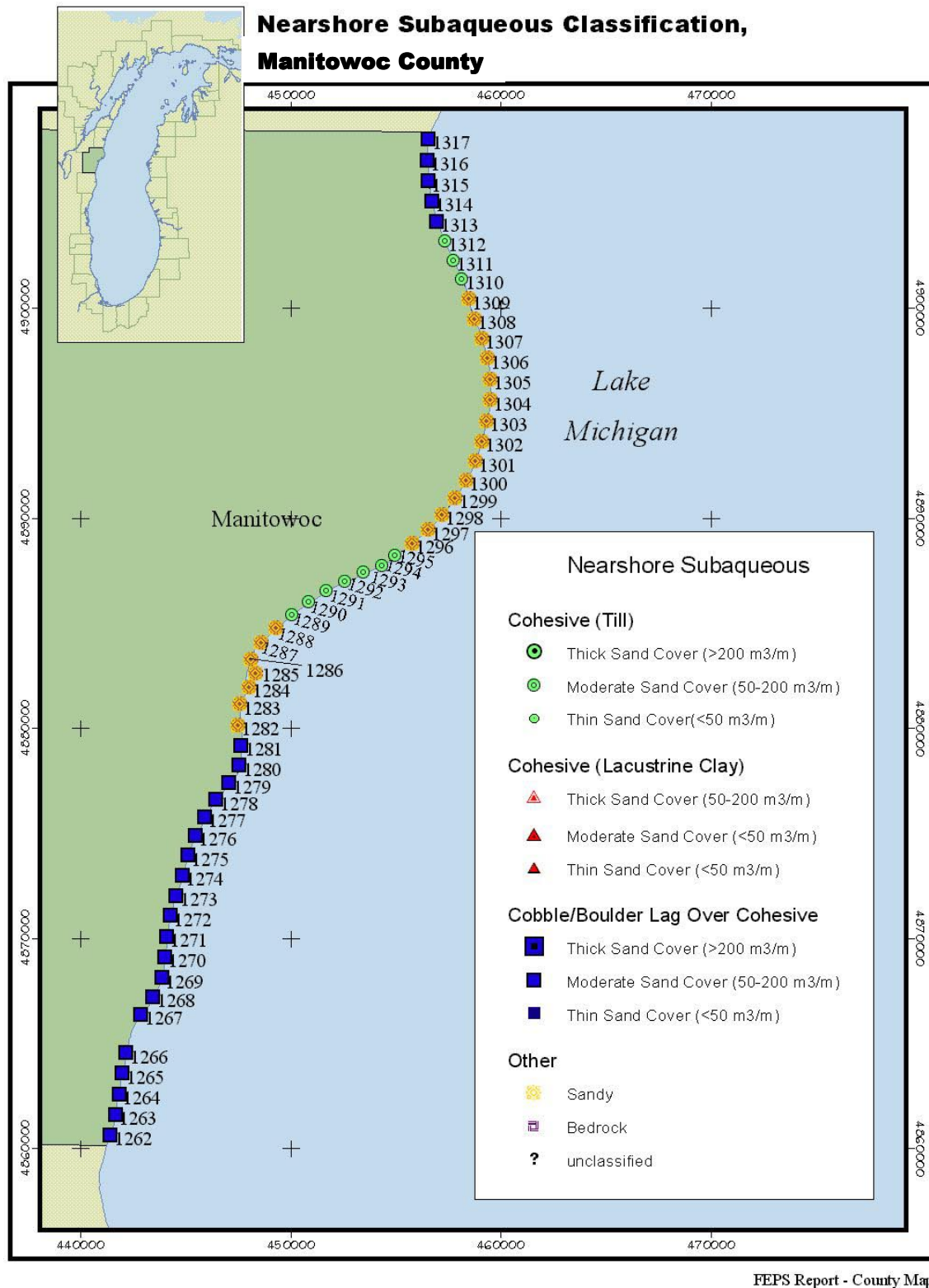


Figure 5.37a Geomorphic Classification for Sheboygan County



**Figure 5.37b Geomorphic Classification for Manitowoc County**





**Figure 5.38b Nearshore Subaqueous Classification for Manitowoc County**

### 5.5.1.2 Single Value Recession Rates

Many of the problems encountered with the SVRR in the previous counties were again observed in northern Sheboygan and Manitowoc. As an example, Table 5.14 lists all of the published annualized erosion rates for Reaches 1273 to 1276, located south of Manitowoc Harbor in a segment of shoreline dominated by the cobble boulder lag lake bed conditions. The magnitude of the annualized erosion rates vary widely for this 4 km section of shoreline, and range from 0.08 to 2.18 m/yr.

**Table 5.14**  
**Sample of Annualized Erosion Rates for Reaches 1273 to 1276 (south of Manitowoc Harbor)**

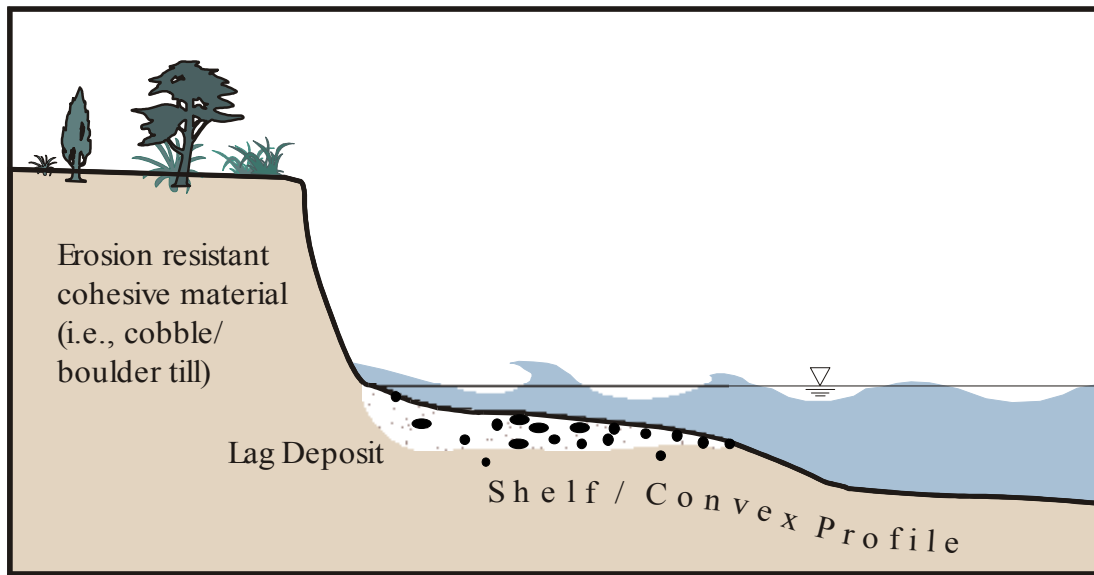
Reach	Annualized Erosion Rate (m/yr)	Number of Samples per Reach	Years of Record	Confidence (1 is high, 4 is low)	Agency
1273	0.34	1	143	3	1835-1978 Peters (1982)
1273	0.85	6	40	3	1938-1978 Peters (1982)
1273	2.18	1	14	2	1978-1992 Bay-Lake RPC (1996)
1274	0.47	4	40	3	1938-1978 Peters (1982)
1274	1.52	1	14	2	1978-1992 Bay-Lake RPC (1996)
1275	0.11	1	143	3	1835-1978 Peters (1982)
1275	0.08	1	142	3	1834-1976 Buckler (1981); Buckler and Winters (1983)
1275	0.41	3	40	3	1938-1978 Peters (1982)
1275	1.42	1	14	2	1978-1992 Bay-Lake RPC (1996)
1276	0.76	2	40	3	1938-1978 Peters (1982)
1276	1.52	1	14	2	1978-1992 Bay-Lake RPC (1996)

The biggest limitation with the use of published erosion rates for the 1 km shoreline reaches in the LMPDS study is the limited number of samples. The average for the eleven AER in Table 5.14 is two erosion transects per 1 km of shoreline. Given the potential bias introduced by bluff slope, one or two erosion measurements over a 1 km section of eroding cohesive shorelines is simply not sufficient to record a representative average annual erosion rate.

In spite of the data limitations, an interesting trend was observed between the AER for two temporal periods: 1) 1938 to 1978 which features a good mixture of high and low lake levels; and 2) 1978 to 1992 which features only very high levels. On average, the short term results from 1978 to 1992 for the high lake level period were 2.7 times greater than the annualized erosion rates for the 1938 to 1978 period. If the accuracy of the published AER is acceptable, the data suggest that erosion of the cobble boulder lag profiles in Sheboygan and Manitowoc is sensitive to lake level fluctuations.

### 5.5.1.3 Historic Profile Comparison – 1913 to 1999

In the summer of 1999 several of the historic profile lines in Manitowoc were re-occupied with differential GPS to collect data for a 1913 to 1999 comparison at a site which featured a cobble boulder lag deposit. Figure 5.37 provides a conceptual sketch of a cobble lag profile, which features a wide distinctive shelf and convex form. The shelf generally forms between the 2 / 3 m depth contour and is armoured with cobbles and boulders from the soil matrix. Recall from Figure 4.4 that the other major cohesive classification is the concave type and the form is approximated by the equilibrium profile.



**Figure 5.37 Conceptual Sketch of a Cobble Boulder Lag Profile**

The primary objective of the survey was to re-occupy several 1913 profiles that featured a cobble boulder lag deposit to investigate the long term evolution of the lake bed. Based on existing hydrographic mapping, Reaches 1263 to 1264 in Cleveland, Wisconsin were selected for the survey. Figure 5.38a captures an exposure of cohesive substrate at the waterline for profile five. Figure 5.38b provides an alongshore view of the site, which is located just north of the Sheboygan Manitowoc County line. Notice the high concentration of boulders and cobbles on the beach and at the waterline.

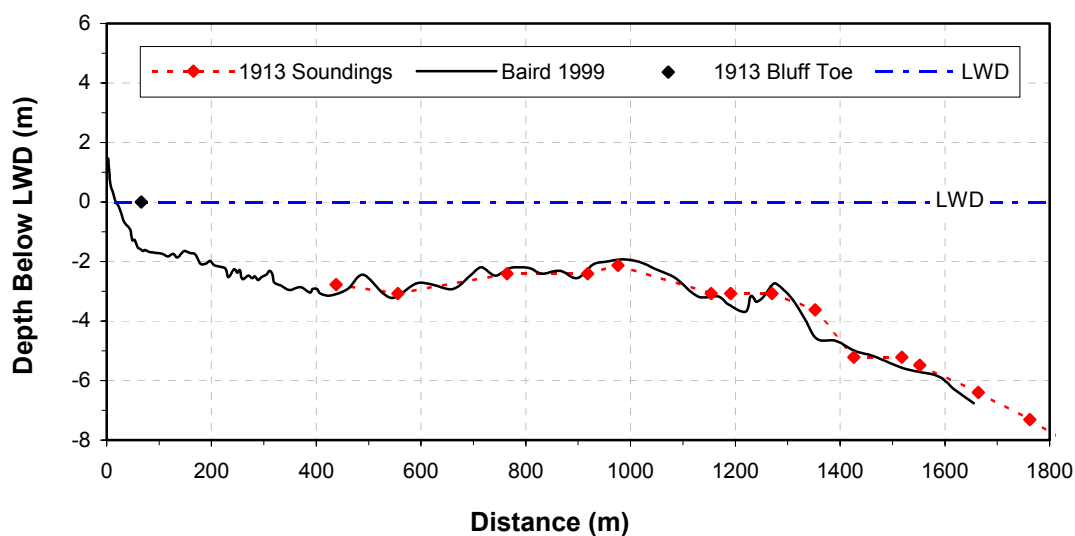


**Figure 5.38a Exposed Cohesive Lake Bed**



**Figure 5.38b Cobbles at the Waterline and on the Beach**

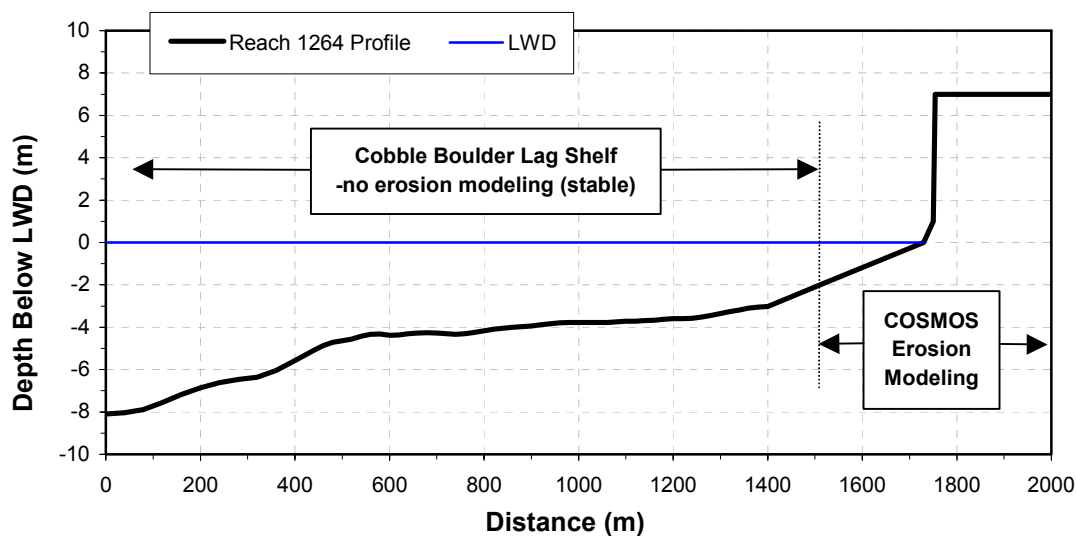
The results of the 1913 to 1999 profile comparison for Reach 1264 are plotted in Figure 5.39. Although the density of the historic survey is limited, especially when compared to the GPS data, the findings record very important information about erosion processes for



**Figure 5.39 1913 to 1999 Profile Comparison at Reach 1264**

the cobble lag profiles. Reach 1264 features a steep swash zone and a very wide shelf that has formed between the 2 and 3 m contour. As the 1913 data indicates, the shelf has been relatively stable for a 1,400 m section of the profile. Unfortunately, the last bathymetry point in the 1913 survey was located approximately 400 m from the waterline, which is noted on Figure 5.39. A comparison of the 1913 waterline to the 1999 survey suggests a long term erosion rate of 0.59 m/yr. This area of limited data coverage represents the active nearshore zone where lake bed downcutting is still ongoing, since the cobble boulder lag deposit has not completely armoured the underlying cohesive sediment.

The results of the historic profile comparison for the Cleveland boulder cobble lag site in Manitowoc provided valuable information on the processes and rates of nearshore downcutting for these profiles. Figure 5.4 summarizes the COSMOS modeling approach based on these findings and our previous knowledge of cobble boulder lag profiles. Over the 50 year modeling horizon, the lake bed offshore of the 2 m depth contour is assumed to be stable (i.e. erosion routines are shut down in the model). Inshore of the 2 m depth contour, the lake bed and bluff erodes.



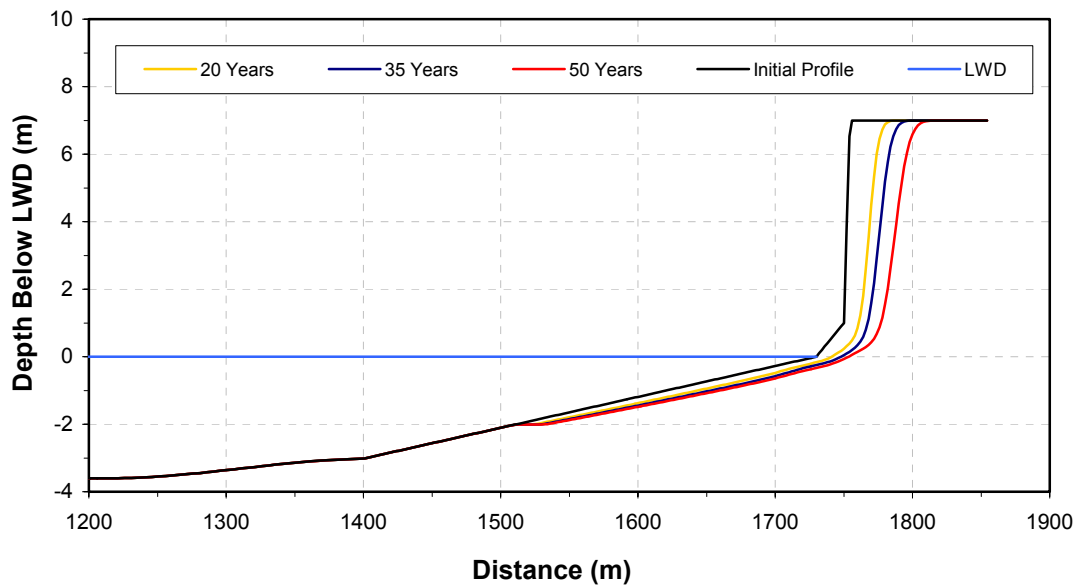
**Figure 5.40 COSMOS Modeling for Cobble Boulder Lag Profiles**

#### 5.5.1.4 Bathymetry and Topography

The SHOALS survey for Sheboygan and Manitowoc was unsuccessful at capturing bathymetry data. Consequently, the 1913 USACE survey was used for regional bathymetric coverage. This data was meshed together with the 1999 toe and top of bank mapping for the COSMOS modeling. Limitations of utilizing the 1913 bathymetry data was outlined in previous sections of the report.

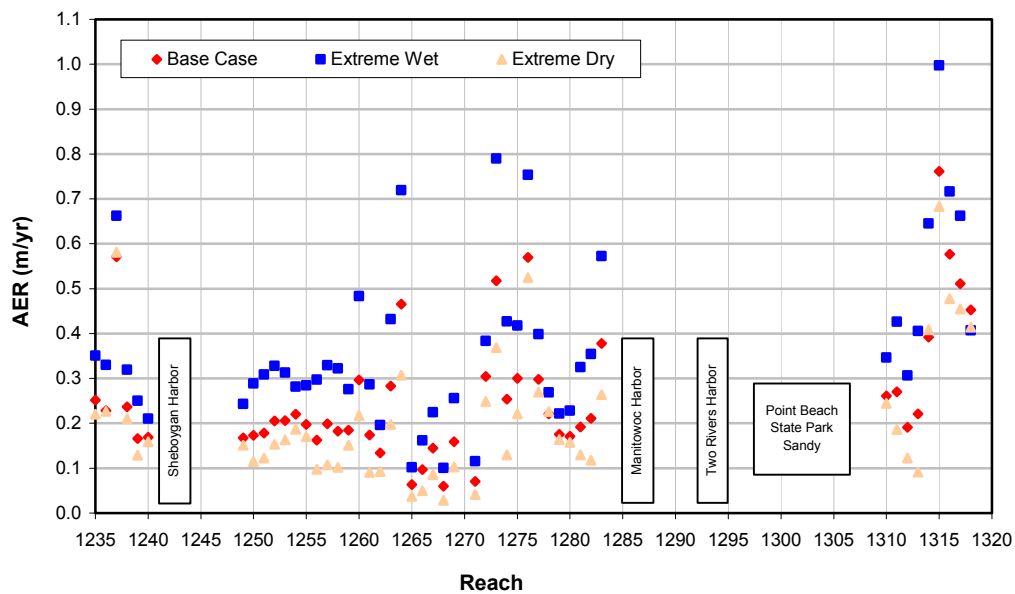
### 5.5.2 FEPS Erosion Modeling

FEPS shore erosion estimates were completed for the cohesive reaches in Sheboygan and Manitowoc County. The results for Reach 1264, which featured a cobble boulder lake bed classification and a SVRR of 0.78 m/yr, is presented in Figure 5.41 for the extreme wet scenario. The erosion estimates from the COSMOS model are plotted at 20, 35 and 50 periods during the simulation. Offshore of the 2 m depth contour, no lake bed erosion is predicted (i.e. erosion routines are shut down in the model).



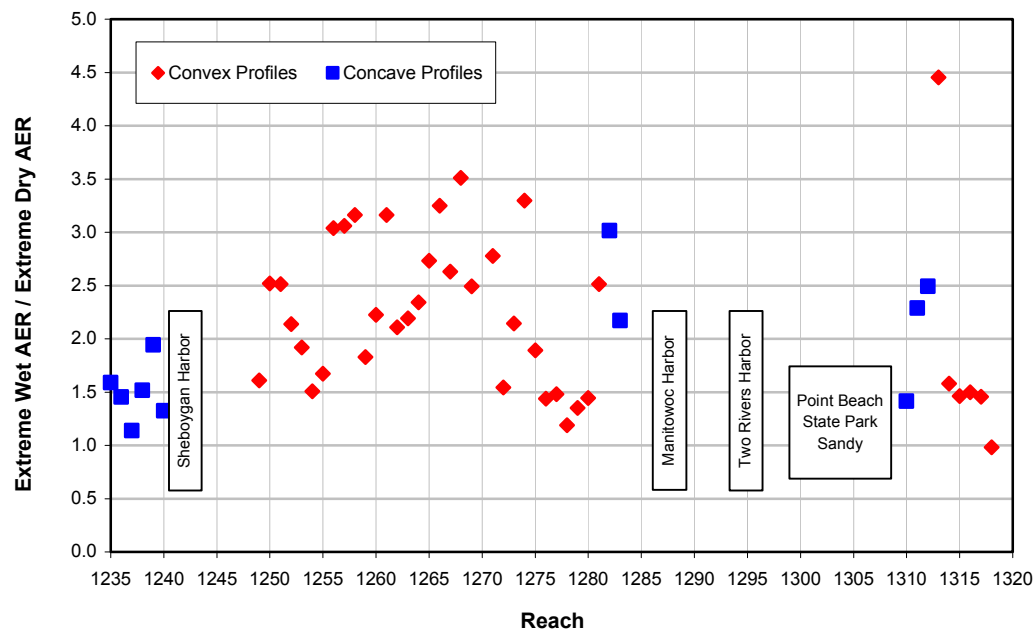
**Figure 5.41 COSMOS Modeling for Cobble Boulder Lag Profiles**

As a summary, Figure 5.42 presents the modeled erosion rates for the cohesive reaches in Sheboygan and Manitowoc for the three LMPDS scenarios. The location of the harbor structures at Sheboygan, Manitowoc and Two Rivers are also noted on Figure 5.42. The sandy reaches for Point Beach State Park were modeled with the sediment budget in the FEPS (discussed in Section 5.6). Top of bank erosion is predicted for all three scenarios, with the highest rates corresponding to the extreme wet scenario and the lowest retreat estimates for the extreme dry scenario. The results in Figure 5.42 include 38 convex or cobble lag profiles and 11 concave or equilibrium type profiles.



**Figure 5.42 COSMOS Erosion Estimates for the Three LMPDS Scenarios**

Erosion sensitivity for the 49 cohesive reaches is further investigated in Figure 5.43, which plots the ratio between the extreme wet and dry modeled erosion rates for the convex and concave profiles. The convex profiles (cobble lag), which were focused between the harbors at Sheboygan and Manitowoc, exhibited a high sensitivity to lake



**Figure 5.43 Ratio Between Model Results for Extreme Wet vs Extreme Dry (concave and convex profiles)**

levels, with the results for the extreme wet scenario ranging from 1.5 to 3.5 times greater than the extreme dry scenario. The results appear to support the published AER in Table 5.15, which indicate the 1978 to 1992 erosion rates for the high lake level period were 2.7 times greater than the long term rates from 1938 to 1978.

It is important to note that there are concerns about two critical datasets utilized in the modeling, namely the SVRR and the lake bed bathymetry. As such, the results in Tables 5.42 and 5.43 are preliminary.

### **5.5.3     *Summary and Recommendations***

Reaches 1235 to 1318 were primarily classified as cohesive shorelines, with both concave and convex profiles. The reach boundaries also included three harbors, a section of low bank that was armoured with Level 1 protection and not modeled (Reach 1287 to 1294), and an isolated sandy shore section (Point Beach State Forest). As with other reaches in Wisconsin, there were significant limitations with the geo-spatial datasets and consequently the modeling results are preliminary. A summary of the major findings is listed, along with recommendations:

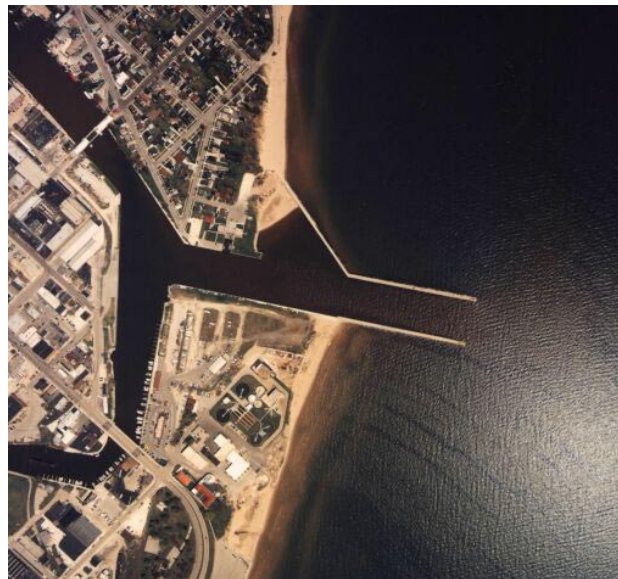
1. Although the published erosion rate data for the cohesive reaches covered a wide range of temporal periods, the sampling density was not sufficient to record a defensible long term annualized erosion rate that is representative for the 1 km reaches;
2. Detailed toe and top of bank GIS mapping is required for several historic epochs to calculate detailed reach specific annualized erosion rates for periods of high and low lake levels;
3. The 1913 to 1999 historic profile comparison for the cobble boulder lag site at Reach 1264 provided valuable insight into the long term evolution and erosion of these profile types. The results indicate that once sufficiently armoured, the cobble boulder lag shelf is stable and erosion is limited to the shallow nearshore zone from the waterline to the 2 / 3 m depth contour;
4. Recent bathymetry data is required to assess lake bed erosion rates for additional cobble lag profiles and provide a baseline for the COSMOS erosion modeling;
5. Top of bank erosion was predicted for all three LMPDS scenarios over the 50 year modeling period for the preliminary results. The highest annualized erosion rates were recorded for the extreme wet scenario, while the rates for the extreme dry were generally 1.5 to 3 times lower; and

6. Once recent bathymetry data is collected and reach specific annualized erosion rates are calculated, the COSMOS erosion modeling should be redone for the cohesive reaches in northern Sheboygan and Manitowoc Counties.

## **5.6 Manitowoc Point Beach State Forest – Sediment Budget 1297 to 1309**

The northern third of Manitowoc County, from Reach 1297 to 1309 was classified as a sandy shoreline and lake bed. Refer to Figures 5.37b and 5.38b for detailed mapping of the 1 km reach classification. The sandy reaches are located in Point Beach State Forest. Beach ridges on the topographic mapping suggest that Point Beach is a depositional features, possibly due to the convergence of longshore sediment transport from the north and south.

The harbor jetties at Two Rivers are located in Reach 1295, 2 km south of the southern sandy reach. A 1992 aerial photograph of the harbor jetties is presented in Figure 5.44. Deposition in the fillet beaches suggests the net longshore sediment transport rate is towards the north east. North of Reach 1309, the shoreline is backed with cohesive bluffs and a combination of glacial till and cobble lag lake bed. Kewaunee Harbor is located in Reach 1334, 25 km north of Point Beach State Forest. At Kewaunee, the north and south fillet beaches suggest the direction of net longshore sediment transport is to the north.



**Figure 5.44 Two Rivers**

The FEPS application at Point Beach is discussed, including the coastal data, the sediment budget modeling, a summary of findings and recommendations.

### **5.6.1 Coastal Data**

The coastal data utilized in the FEPS application is discussed for Point Beach and the adjacent shorelines to the north and south.

### 5.6.1.1 Single Value Recession Rates

The published single value recession rates for Reaches 1297 to 1309 are summarized in Table 5.15. The confidence ranking (column five) ranges from 3 to 4, with 4 being the lowest possible rating. The Wisconsin CZM data only provides a range (i.e. less than 0.61 m/yr or 2 ft/yr), not an actual rate of shoreline recession, which is why the confidence ranking is low (i.e. 4). The relatively low confidence ranking for the SHE and Baker (1997) data is due to the calculation methods.

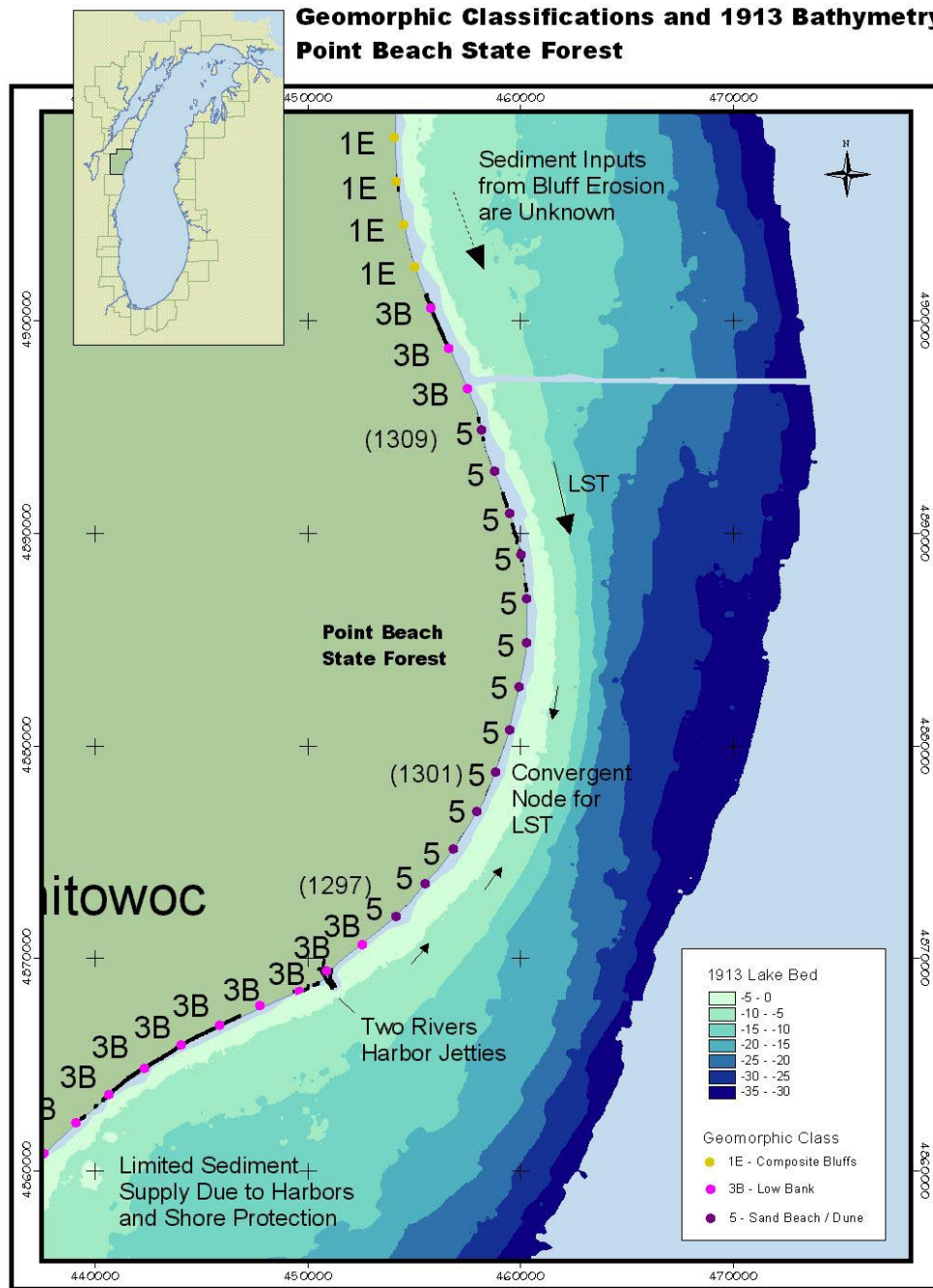
**Table 5.15**  
**Published Annualized Erosion Rates for Reaches 1297 to 1309 - Point Beach State Park**

Reach	AER (m/yr)	# of Samples per Reach	Years of Record	Confidence (1 is high, 4 is low)	Agency	Selected AER Based on FEPS Modeling
1297	<.61			4	Wisconsin CZM 1979 MAP	0.00
1298	<.61			4	Wisconsin CZM 1979 MAP	0.00
1299	<.61			4	Wisconsin CZM 1979 MAP	0.00
1300	<.61			4	Wisconsin CZM 1979 MAP	0.00
1301	<.61			4	Wisconsin CZM 1979 MAP	0.00
1302	0.03	3	40	3	1952-1992 SEH and Baker (1997)	0.00
1302	<.61			4	Wisconsin CZM 1979 MAP	
1303	0.30	17	40	3	1952-1992 SEH and Baker (1997)	0.30
1303	<.61			4	Wisconsin CZM 1979 MAP	
1304	0.05	16	40	3	1952-1992 SEH and Baker (1997)	0.00
1304	<.61			4	Wisconsin CZM 1979 MAP	
1305	-0.01	16	40	3	1952-1992 SEH and Baker (1997)	0.00
1305	<.61			4	Wisconsin CZM 1979 MAP	
1306	0.05	16	40	3	1952-1992 SEH and Baker (1997)	0.00
1306	<.61			4	Wisconsin CZM 1979 MAP	
1307	0.58	16	40	3	1952-1992 SEH and Baker (1997)	0.58
1307	<.61			4	Wisconsin CZM 1979 MAP	
1308	0.70	16	40	3	1952-1992 SEH and Baker (1997)	0.70
1308	<.61			4	Wisconsin CZM 1979 MAP	
1309	0.63	17	40	3	1952-1992 SEH and Baker (1997)	0.63
1309	<.61			4	Wisconsin CZM 1979 MAP	

Consequently the data quality for the 13 reaches was not of acceptable accuracy for the application of the FEPS. From Reach 1297 to 1306 the published AER suggests the long term erosion rate is very low or zero. From Reach 1307 to 1309 in the north, the AER vary from 0.58 to 0.70 m/yr. Also, there was insufficient temporal information on historic AER to investigate the influence of rising and falling lake levels on cross-shore erosion processes at Point Beach. However, given the important influence of lake levels on cross-shore processes at other sandy sites in the Prototype Counties, it is likely an important process.

### 5.6.1.2 Bathymetry and Topography

Historic bathymetry for northern Manitowoc County was provided by three 1913 field sheets (1196, 1208, and 1209) which were available from the NOS GEODAS CD. The point data was imported into GIS and used to create 3D lake bed surfaces. The color contours for the 1913 lake bed bathymetry at Point Beach State Forest are presented in Figure 5.45,



**Figure 5.45 1913 Lake Bed Bathymetry for Northern Manitowoc**

along with the geomorphic shoreline classification for the 1 km reaches. Based on the orientation of the nearshore contours, the bathymetry data also suggests that the sandy beaches and dunes are related to the convergence of longshore sediment transport.

In the absence of a recent SHOALS dataset for Point Beach, the 1913 bathymetry was used by the FEPS to extract 2D lake bed profiles. It was not possible to complete a historic to recent lake bed comparison to assess erosion and deposition patterns in northern Manitowoc, which would have provided valuable insight into the long term evolution of this geomorphic feature. Without recent bathymetry or SVRR of acceptable quality, there is no reliable existing data on historic erosion trends for Point Beach State Forest.

The 1999 topographic dataset provided coverage for roads, buildings, toe and crest of dune and coastal structures. This topographic data was combined with the 1913 bathymetry to create input beach profiles for the COSMOS model.

### **5.6.2     *Sediment Budget Modeling***

With the absence of recent bathymetry coverage and SVRR of acceptable accuracy, detailed sediment budget modeling was not possible to investigate sources and sinks for sediment at Point Beach State Forest. However, longshore sediment transport estimates were completed for the base case scenario and hindcasted winds at WIS Station 18 (Baird Software).

#### **5.6.2.1   *Longshore Sediment Transport Rates***

Table 5.17 lists the COSMOS longshore sediment transport rates for Reaches 1297 to 1309 with a 0.2 mm grain size and the base case lake levels. The northern and southerly components of potential LST are provided, along with the net transport direction and volume. From 1297 to 1300, the net transport is directed to the north and decreases from 43,400 m<sup>3</sup>/yr to zero at Reach 1300. From Reach 1309 to 1301, the 1 km reaches also feature a decreasing net gradient, which converges at Reach 1300. An example of the cross-shore distribution for the northerly and southerly component of longshore sediment transport at Reach 1306 is presented in Figure 5.46.

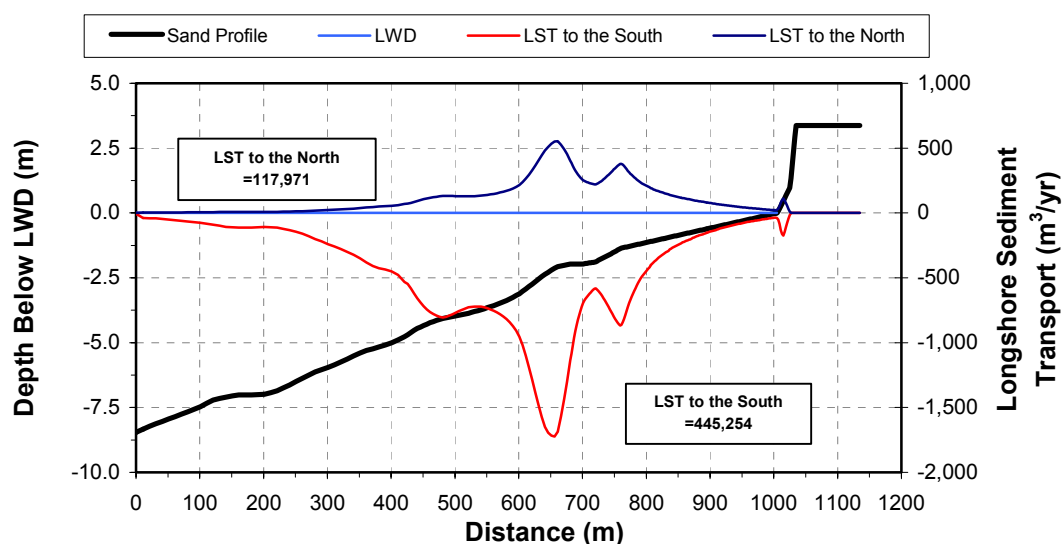
The COSMOS longshore sediment transport results are consistent with the observations of depositional beach ridges in the State Forest and the lake bed conditions from the 1913 bathymetry. However, due to the age of the bathymetric data and lack of sediment grain size information, the results are considered preliminary. Reach specific long term annualized erosion rates are also required to confirm historic rates of change for the State Forest.

**Table 5.16**

**COSMOS Longshore Sediment Transport Estimates, Base Case Scenario**  
(0.2mm grain size)

Reach	Azimuth	LST to the North (m <sup>3</sup> /yr)	LST to the South (m <sup>3</sup> /yr)	Net LST (m <sup>3</sup> /yr)	Direction of Net LST
1297	132	142,573	-99,150	43,423	N
1298	132	142,418	-98,562	43,855	N
1299	123	139,900	-125,141	14,759	N
1300	117	154,315	-154,231	85	N
1301	111	139,771	-162,533	-22,763	S
1302	109	147,626	-186,564	-38,937	S
1303	100	133,999	-267,985	-133,986	S
1304	95	132,542	-327,242	-194,701	S
1305	90	131,766	-372,821	-241,055	S
1306	83	117,971	-445,254	-327,283	S
1307	76	105,807	-480,711	-374,904	S
1308	71	101,800	-514,283	-412,483	S
1309	71	105,044	-523,871	-418,827	S

Temporal issues regarding the sediment budget were not investigated. For example, the lake bed bathymetry is almost 90 years old and considerable changes in sedimentation and erosion patterns could have occurred since the data was collected. For example, south of Point Beach the harbor structures at Two Creeks and Manitowoc, combined with the presence of shore protection have likely resulted in a significant decrease in the long term supply of sediment from the south. Similarly, the harbor at Kewaunee and other shore protection installations at the Point Beach and Kewaunee Nuclear Power Plants may have also impacted the sediment supply rates to Point Beach.



**Figure 5.46 Cross-shore Distribution of Northerly and Southerly LST (Reach 1306)**

#### *5.6.2.2 Summary of Findings*

Due to the absence of several critical datasets, it was not possible to complete a full sediment budget application at Point Beach. However, based on the preliminary modeling results, the following summary is provided:

1. A convergent longshore sediment transport node was identified at Reach 1300, which is consistent with observations from the topographic and bathymetric data;
2. Additional information on sediment grain size is required to confirm the magnitude of the sediment transport estimates in Table 5.17;
3. Potential LST rates may be considerably greater than the actual supply from shore erosion, especially for the area north of Reach 1309. This would explain the erosion rates for Reaches 1307 to 1309, which average 0.6 m/yr, while the southern half of the State Forest appears to be stable (based on the published erosion rates); and
4. Cross-shore lake level effects were not investigated at Point Beach and may have a significant impact on short term shoreline change rates during rising and falling water levels.

#### *5.6.3 Recommendations*

Based on the FEPS application at Point Beach State Forest and the summary provided in the previous section, the following recommendations for further data acquisition and modeling are provided:

1. Detailed bathymetric data of the existing lake bed conditions is required. Once collected, a regional 1913 to present 3D lake bed comparison is required;
2. Top and toe of dune mapping is required for several epochs over a range of lake level conditions and long temporal periods. Then, reach specific shoreline change rates could be calculated with the FEPS;
3. Sediment grain size information is required for Point Beach at several locations and in a cross-shore direction (i.e. the COSMOS model can vary sediment grain size across the profile);
4. The influence of harbors and shore protection on the supply of new littoral sediment to Point Beach must be determined to investigate temporal issues related to the sediment budget;

5. A second FEPS application is required to quantify all sources and sinks of sediment at Point Beach and confirm the reach specific historic shoreline change rates; and
6. A Bruun Rule type module is required to model the cross-shore influences of the three LMPDS lake level scenarios.

## **6.0 GIS MAPPING OF FUTURE SHORELINE POSITION**

The detailed FEPS modeling for the five prototype counties was presented in Section 5.0 of the report. With the prediction of 50 year erosion rates for the three LMPDS scenarios, the final task was the GIS mapping of future shoreline position. Section 6.0 will discuss the temporal scale for the estimates of future shoreline position, incorporation of the detailed shore protection classification, a discussion of the GIS algorithms for cohesive and sandy shorelines, and delivery of county wide future top of bluff lines.

### **6.1 Temporal Scale for Mapping of Future Shoreline Position**

The temporal scale for the analysis of the three LMPDS scenarios was 50 years. In addition to the future 50 year top of bank (or dune crest) line, two intermediate estimates were provided at 20 and 35 years. The 1999 topographic mapping for the prototype counties (toe and top of bank) was used as the starting point for the future estimates.

### **6.2 Consideration of Shore Protection**

The shoreline classification was expanded in the five prototype counties to include 100 m descriptions of the type (i.e. revetment) and projected life span (i.e. >45 years) of the shoreline protection tier. Based on this 100 m detail, a set of rules was developed to consider the data when forecasting future shoreline estimates with the FEPS (i.e. 50 year top of bluff lines). The following rules apply to both cohesive and sandy shore reaches:

1. If Level 1 protection is longer than 50 m within a 100 m sub-reach, the 100 m sub-reach will not erode;
2. If the Level 1 protection is only 50 m or less within a 100 m sub-reach, then the protection is ignored;
3. If a 1 km reach has greater than 800 m of Level 1 protection, then the entire reach will be stable and no erosion will be predicted for the 50 year projections;
4. If Level 2 protection covers 800 m or more of continuous shoreline, the shore will not erode for the 50 year predictions. The eight continuous 100 m sub-reaches can be contained within a reach or extend across a reach boundary;
5. Harbors and jetties must be examined with judgment. For example, if a 2B1 jetty (>45 year life span) runs parallel to the shore in a 100 m sub-reach, the shore may be stable over the 50 year planning horizon. Also, the presence and influence of stable fillet beaches adjacent to harbors and jetties must be evaluated individually;

6. Under all other conditions, existing shore protection is ignored on a 100 m basis.

The above set of rules provides a conservative approach to accounting for the erosion protection provided by coastal structures in the prototype counties. Based on the application of the rules in the five counties and future FEPS modeling in additional counties, minor modifications may be required.

### **6.3 GIS Mapping of Future Shoreline Position**

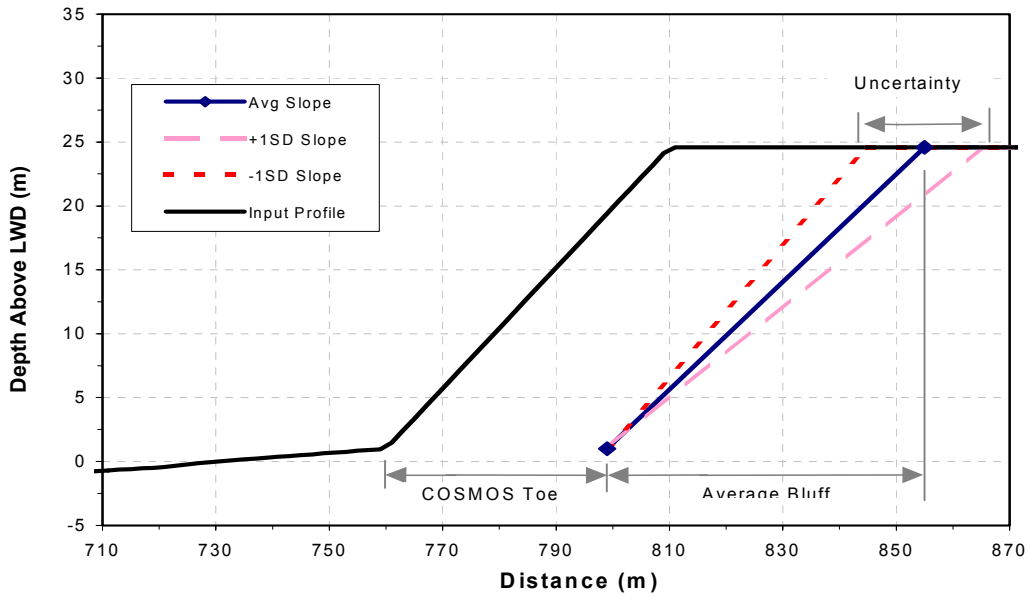
Separate methodologies were developed to map future shoreline position for cohesive and sandy shorelines, as outlined in Section 4.2 of the report. The GIS tools in the FEPS to map future shoreline position for cohesive and sandy shores were discussed in Sections 2.2.7.3 and 2.2.7.4 respectively. Examples of future shoreline estimates for the cohesive and sandy reaches are provided.

#### **6.3.1 *Future Shore Algorithm for Cohesive Reaches***

The methodology to model cohesive shore erosion was discussed in Section 4.2.2 of the report. Results of the COSMOS erosion estimates for cohesive shorelines were provided in Section 5.0. The final step in the FEPS application to predict future shoreline position is to convert the 2D COSMOS model results (i.e. annualized erosion rates) to 1 km estimates of top of bank position at 20, 35 and 50 year intervals.

The Create Future Shore Tool, discussed in Section 2.2.7.3, is utilized to query the coastal database on a reach by reach basis and establish the horizontal setback distance for the future top of bank lines. Figure 6.1 summarizes the modeling results used in the GIS to map the results of the COSMOS modeling, which follows four general steps:

1. First, the tool is launched and the 1999 toe and top of bank lines are loaded in ArcView for a specified reach;
2. The COSMOS output file is located in the coastal database for each scenario and the estimate of toe erosion is extracted at 20, 35 and 50 years. These horizontal distances are measured from the bluff toe;
3. Then, the average bluff slope is added to the setback distance; and
4. Finally, the width of the uncertainty band is determined based on +/- 1 standard deviation units (m) of the horizontal bluff slope distance.



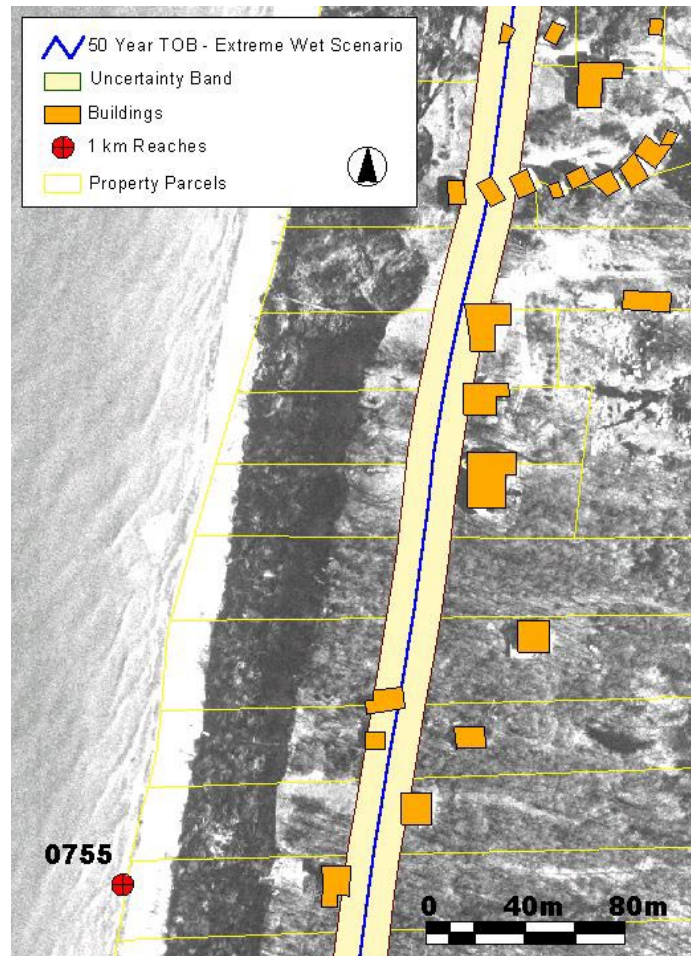
**Figure 6.1 Future Top of Bank Algorithm for Cohesive Shores**

The COSMOS model predictions are measured from the toe of bank to eliminate the bias introduced by bluff slope (i.e. as opposed to starting the measurements from the top of bank). The uncertainty band (step 4) provides a range for the 50 year top of bank position due to the inability to predict bluff slope conditions 50 years in the future. An example of the 50 year top of bank estimates for the three LMPDS scenarios is presented in Figure 6.2 for Reach 0755. The extreme wet scenario resulted in the greatest amount of top of bank retreat, while the extreme dry scenario featured the least amount of erosion.



**Figure 6.2 50 Year Top of Bank Lines, Reach 0755**

Figure 6.3 presents the 50 year top of bank line for the extreme wet scenario and the polygon associated with the uncertainty band. The width of the uncertainty band is based on the recorded variability in the 1999 bluff slope data on a reach by reach basis. For example, reaches with a wide range of slope conditions over the 1 km segment will have a wide uncertainty band to account for the range of potential slope conditions that may occur 50 years in the future.



**Figure 6.3 50 Year Top of Bank with Uncertainty Band**

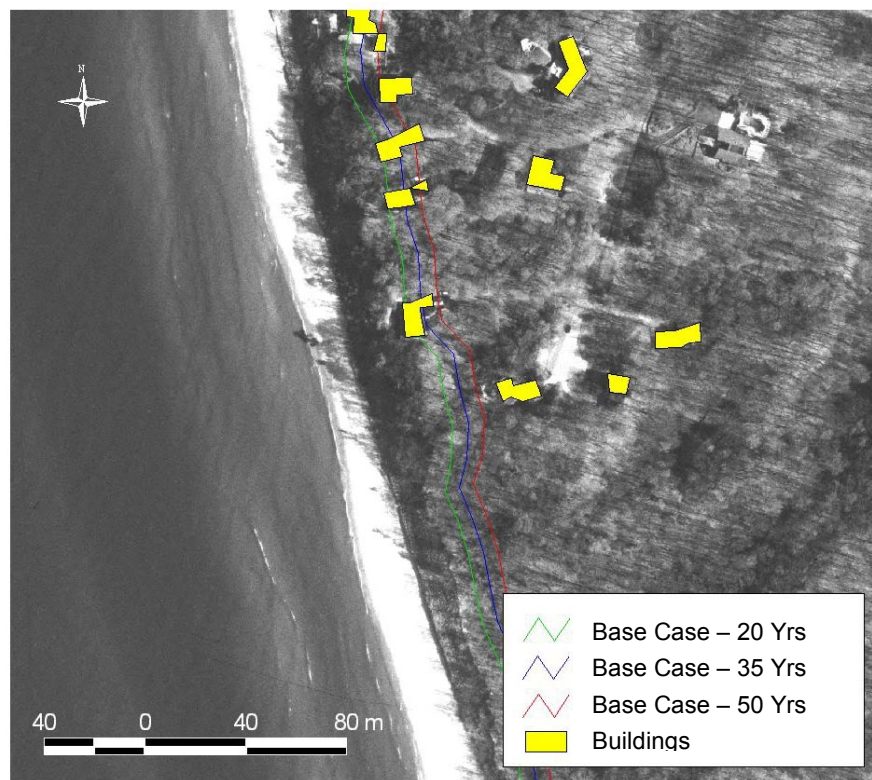
### **6.3.2 Future Shore Algorithm for Sandy Reaches**

The sediment budget tools in the FEPS were applied to three distinctive sandy environments on Lake Michigan, including: 1) eroding relic sand dunes in Ottawa County; 2) relatively stable sandy low banks with a bedrock lake bed in northern Ozaukee and southern Sheboygan Counties; and 3) a large depositional feature associated with convergent LST in northern Manitowoc County, which forms Point Beach State Forest.

Collectively, the geo-spatial data in the coastal database and the analysis tools associated with the various modules in the Flood and Erosion Prediction System were used to predict and quantify sinks and sources of sediment. For all three sandy units described above, the sediment budget was not closed due to insufficient data on historic shoreline change rates and existing bathymetric conditions. However, to the extent possible, the results of the FEPS analysis were used to confirm the accuracy of the published shoreline change rates or select a more appropriate value.

The ArcView ‘Create Future Sandy Shoreline’ tool, which was described in Section 2.2.7.4, was used to map future shoreline position for the 50 year planning horizon based on the results of the sediment budget and the published SCR. The input menu for the tool was presented in Figure 2.15.

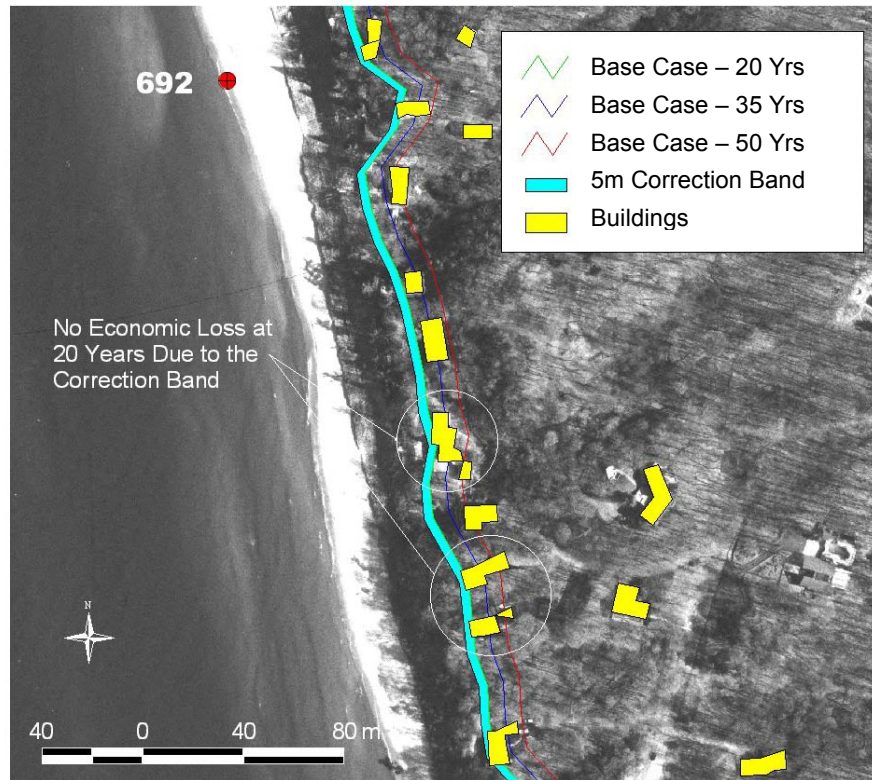
A sample of the FEPS output for Reach 692 is presented in Figure 6.4 for the base case scenario. The 20, 35 and 50 year top of dune lines are presented with an ortho-photo backdrop. Several of the existing lakefront buildings, highlighted with yellow shading, are predicted to suffer erosion damage in less than 50 years in this particular example.



**Figure 6.4 20, 35, and 50 Dune Crest Lines for the Base Case Scenario**

Significant cross-shore lake level induced erosion and recovery was recorded in the historic erosion rates in the prototype counties. This data was utilized to develop a preliminary methodology to account for the significant changes in monthly mean lake levels between the three LMPDS scenarios. Table 5.8 summarized the correction bands that were applied to the 20, 35 and 50 year top of dune estimates based on the sediment budget results. A sample of the 5 m lakeward correction band for Reach 0692 is presented in Figure 6.5. For the base case scenario there was a 5 m lakeward correction in the top of dune position applied to the 20 year prediction, which is mapped as the shaded polygon in the Figure 6.5. The significance of the correction band is noted for the buildings circled in Figure 6.5. Without the correction, the buildings would be destroyed

by erosion and thus considered in the economic damage estimate. However, when the 5 m correction band is applied, the homes are not threatened or damaged by erosion at year 20.



**Figure 6.5 5 m Lakeward Correction Band for 20 Year Prediction (Base)**

#### **6.4 Delivery of Future Top of Bank Lines for the Counties**

Once the future top of bank lines and dune crest was mapped for all reaches in the prototype counties, they were merged into one continuous county line / polygon coverage for the individual temporal periods and lake level scenarios. The lines were delivered as ArcView shape files.

## **7.0 RECOMMENDATIONS**

The Flood and Erosion Prediction System was applied to 228 reaches in the five prototype counties to predict future shoreline position in response to the three LMPDS lake level scenarios. In total, over 2,000 km of GIS mapping was generated with the tools in the FEPS. Based on the results of the FEPS application discussed in Section 5.0, several recommendations have been provided for additional data acquisition, upgrades to the modules in the FEPS and future application of the system in the prototype counties.

### **7.1 Data Acquisition**

The results of the FEPS application in the prototype counties has highlighted the critical importance of detailed topographic and bathymetry data to make defensible estimates of shoreline response to the three LMPDS lake level scenarios. The topographic mapping collected in 1999 was of sufficient detail to record the existing reach conditions in the prototype counties. However, in all five prototype counties, the SVRR and additional published annualized erosion rates were of unacceptable quality for the FEPS modeling. Therefore, it is recommended that detailed toe and top of bank / dune crest mapping be collected for the prototype counties for several epochs and covering periods of high, average and low lake levels.

The SHOALS system provided detailed bathymetry data in Allegan and southern Ottawa County. However, for the northern half of Ottawa, in the vicinity of some harbors and for all three Wisconsin Counties the SHOALS system was unsuccessful in acquiring bathymetric data. Therefore, in the absence of recent regional bathymetric coverage, various historic surveys were used to generate model inputs (i.e. 1913 and 1948). The absence of recent bathymetry was a significant modeling limitation and it is recommended the counties without coverage be re-surveyed.

### **7.2 FEPS System Development**

Based on the results of the FEPS application to over 200 km of shoreline on Lake Michigan, several recommendations are provided to develop additional modules, enhance existing system capabilities, and upgrade the online help. The following bullets summarize the recommended system upgrades to improve the efficiency of the model application:

- Upgrade the COSMOS code to decrease model run time and improve the efficiency of the FEPS applications;

- Develop a new module to automate the calibration process for the cohesive erosion modeling with COSMOS;
- A new Bruun Rule Type Module is required to develop a defensible methodology to account for cross-shore lake level influences related to the LMPDS scenarios; and
- The development of Online Help and Installations Shields is recommended for the FEPS interface and modules;

### **7.3 FEPS Modeling in the Prototype Counties**

Recommendations are provided for future modeling in the five prototype counties with the Flood and Erosion Prediction System based on the results of the applications presented in Section 5.0 of the report.

#### **7.3.1 *Ottawa and Northern Allegan – Sediment Budget***

The sediment budget did not close for the sandy reaches in Ottawa and Northern Allegan due to uncertainties about inputs from shore erosion and sinks offshore of the harbors. Detailed top and toe of dune mapping is recommended to verify sediment budget inputs from shore erosion. Also, sediment sinks offshore of the harbor jetties must be confirmed with additional bathymetric data collection. Once these two key variables are confirmed, the sediment budget module should be re-applied to the sandy reaches in Ottawa and Allegan Counties.

#### **7.3.2 *Allegan County – Cohesive Modeling***

Detailed shore erosion modeling was completed for the cohesive reaches in Allegan County. However, due to the limited spatial resolution of the historic erosion rate data, there is poor confidence in the published SVRR in the shore classification. Detailed reach specific top and toe of bank mapping is required for several historic epochs. Then, the GIS tools in the FEPS can be applied to calculate reach specific annualized erosion rates. If significant discrepancies exist between the SVRR data and the annualized erosion rates calculated with the FEPS, the cohesive modeling in Allegan should be completed again.

### **7.3.3     *Ozaukee County – Cohesive Modeling***

COSMOS model predictions of future shore erosion rates were completed for the cohesive reaches in Ozaukee County for the three LMPDS scenarios. However, the results are considered preliminary due to limitations with the SVRR and a lack of recent regional bathymetric data. Detailed reach specific annualized erosion rates are required, along with detailed existing bathymetric coverage. Once this data is collected, the FEPS should be re-applied.

### **7.3.4     *Northern Ozaukee and Southern Sheboygan – Sediment Budget***

The absence of recent bathymetric data was a significant limitation for the sediment budget modeling for the low bank reaches in northern Ozaukee and southern Sheboygan County. Based on the preliminary application of the FEPS, the shore appears to be stable with the exception of cross-shore profile adjustments due to lake level fluctuations (i.e. high to low levels).

Detailed existing bathymetric data is required to investigate lake bed changes since the 1913 survey and confirm the presence bedrock. Also, detailed top and toe of bank mapping is required prior to re-applying the FEPS.

### **7.3.5     *Northern Sheboygan and Manitowoc Counties – Cohesive Modeling***

The cohesive modeling for Sheboygan and Manitowoc Counties is preliminary due to limitations with the SVRR and the use of the 1913 bathymetry. Once additional data is collected, the FEPS should be re-applied to predict the influence of the three LMPDS lake level scenarios on shore erosion rates.

### **7.3.6     *Manitowoc Point Beach State Forest – Sediment Budget***

The sediment budget modeling identified a convergent node for longshore sediment transport at Point Beach State Forest. Unfortunately, without recent bathymetry data, it was not possible to investigate the historic evolution of the lake bed for the sandy reaches in northern Manitowoc and sediment sinks / sources. Once recent bathymetric data is collected and the validity of the published SVRR is confirmed, the FEPS should be re-applied to the Point Beach State Forest reaches.

## REFERENCES

- Amin, S.M.N. and Davidson-Arnott, R.G.D., 1995. Toe Erosion of Glacial Till Bluffs: Lake Erie South Shore. *Canadian Journal of Earth Sciences*, 32, p.829-837.
- Assel, R.A., Robertson, D.M., Hoff, M.H., and Selgeby, J.H., 1995. Climatic-change Implications for Long-term (1823-1994) Ice Records for the Laurentian Great Lakes. *Annals of Glaciology*, 21, p.383-386.
- Assel, R.A., Janowiak, J.E., Young, S., and Boyce, D., 1996. Winter 1994 Weather and Ice Conditions for the Laurentian Great Lakes. *Bulletin of the American Meteorological Society*, 77-1, p.71-88.
- Baird, 1999. LMPDS – Development and Testing of the Flood & Erosion Prediction System – FY98 Progress. p.1-77.
- Bishop, C., Skafel, M., and Nairn, R., 1992. Cohesive Profile Erosion by Waves. *Proceedings from the Twenty-Third International Conference on Coastal Engineering*, Venice, Italy, p.2976-2989.
- Carter, C.H. and Guy, D.E., 1988. Coastal Erosion: Processes, Timing and Magnitudes at the Bluff Toe. *Marine Geology*, 84, p.1-17.
- Davidson-Arnott, R.G.D. and Ollerhead, J., 1995. Nearshore Erosion of a Cohesive Shoreline. *Marine Geology*, 122, p.349-365.
- Davidson-Arnott, R.G.D., 1986. Rates of Erosion of Till in the Nearshore. *Earth Surface Processes and Landforms*, 11, p.53-58.
- Davidson-Arnott, R.G.D., 1990. The Effect of Water Level Fluctuations on Coastal Erosion in the Great Lakes. *Ontario Geographer*, p.23-39.
- Dean, 1977. Equilibrium Beach Profiles: U.S. Atlantic and Gulf coasts. Department of Civil Engineering, University of Delaware, Technical Report No. 12, p.45.
- Hands, E.B., 1979. Changes in rates of shore retreat, Lake Michigan, 1967-76. Technical Paper No. 79-4, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

- Hubertz, et al. 1991. Wind Waves on the Great Lakes: A 32 Year Hindcast. *Journal of Coastal Research*, 7-4, p.945-967.
- Hudec, P.P., 1973. Weathering of Rocks in Arctic and Sub-arctic Environment. In Aitkens, J.D., and Glass, D.J. (Eds), *Canadian Arctic Geology*, Geological Society of Canada, Canadian Society of Petroleum Geologists Symposium, Saskatoon, p.313-335.
- International Joint Commission, 1993. Methods of Alleviating the Adverse Consequences of Fluctuating Water Levels in the Great Lakes – St. Lawrence River Basin. A Report to the Governments of Canada and the United States, p.1-53.
- Kamphuis, J.W., 1987. Recession Rate of Glacial Till Bluffs. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 113-1, p.60-73.
- Kamphuis, J.W., 1990. Influence of Sand or Gravel on the Erosion of Cohesive Sediment. *Journal of Hydraulic Research*, 28-1, p.43-53.
- King, C.A.M., 1972. *Beaches and Coasts*. Edward Arnold Publishers Ltd., London.
- Komar, P.D., Carpenter, D. and Cougar, W.G., 1995. The application of beach and dune erosion models to the high-energy Oregon coast. Report to the Oregon Department of land conservation and development. p.1-28.
- Komar, P.D., 2000. Coastal Erosion – Underlying Factors and Human Impacts. *Shore & Beach*, 68-1, p.3-16.
- Meadows, G.A. et al, 1997. The Relationship Between Great Lakes Water Levels, Wave Energy and Shoreline Damage. *Bulletin of the American Meteorological Society*, Vol. 87, No. 4.
- MNR, 1988. Littoral Cell Definition and Sediment Budget for Ontario's Great Lakes. Report Prepared for Ministry of Natural Resources, Conservation Authorities and Water Management Branch by F.J. Reinders and Associates Canada Limited.
- Montgomery, W.W., 1998. Groundwater Hydraulics and Slope Stability Analysis: Elements for Prediction of Shoreline Recession. Western Michigan University Ph.D. Thesis, p.183.

- Nairn, R.B., et al, 1986. Physical Modeling of Wave Erosion on Cohesive Profiles. Proceedings from the Symposium on Cohesive Shores, National Research Council Canada, p.210-224.
- Nairn, R.B., 1986. Cohesive Profile Development Model. Proceedings from the Symposium on Cohesive Shores, National Research Council Canada, p.246-261.
- Nairn, R.B., 1992. Erosion Processes Evaluation Paper. Final Report for the International Joint Commission Great Lakes – St. Lawrence River Levels Reference Study Board. Submitted to Environment Canada, Water Planning & Management Branch, Burlington, Ontario.
- Nairn, R.B., Zuzek, P., Morang, A., and Parson, L., 1997. Effectiveness of Beach Nourishment on Cohesive Shores, St. Joseph, Lake Michigan. Technical Report CHL-97-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Nairn, R.B., 1990. Predictions of cross-shore sediment transport and beach profile evolution. Ph.D. thesis, Dept. of Civil Engineering, Imperial College of London.
- Nairn, R.B. and Southgate, H.N., 1993. Deterministic Profile Modelling of Nearshore Processes. Part 2. Sediment Transport and Beach Profile Development. Coastal Engineering, Elsevier. Vol. 19. p.57-96.
- Philpott, K.L., 1983. Lake Erie Nearshore Bottom Profile Comparison, 1896-1979, Port Glasgow to Long Point. Draft Report Prepared for the Deputy Attorney General of Canada, Keith Philpott Consulting Limited (unpublished).
- Philpott, K.L., 1984. Comparison of Cohesive Coasts and Beach Coasts. Proceedings of Coastal Engineering in Canada, Queens University, Kingston.
- Schoonees, J.S. and Theron, A.K., 1995. Evaluation of 10 cross-shore sediment transport/morphological models. Coastal Engineering, Elsevier. Vol. 25. Pp 1-41.
- Southgate, H.N. and Nairn, R.B. (1993). Deterministic Profile Modelling of Nearshore Processes. Part 1. Waves and Currents. Coastal Engineering, Elsevier. Vol. 19. p.27-56.
- Stewart, C.J., 1997. Recession Rate and Land Use Analysis and the Development of an Automated Recession Rate Analysis System – Lake Michigan Potential Damages Study. Report prepared for the U.S. Army Corps of Engineers – Detroit District and Coastal and Hydraulics Lab. p.1-57.

Sunamura, T., 1992. Geomorphology of Rocky Coasts. John Wiley & Sons Ltd., p.302.

Trenhaile, A.S., and Mercan, D.W., 1984. Frost Weathering and the Saturation of Coastal Rocks. Earth Surface Processes and Landforms, 9, p.321-331.

Trenhaile, A.S., 2000. Modeling the Development of Wave-cut Shore Platforms. Marine Geology, 166, p.163-178.

United States Army Corps of Engineers (USACE), 1999. Lake Michigan Potential Damages Study, Progress Report on Activities – 1996-1998. Report Compiled and Edited by VGI Vision Group International Inc., p.67.

United States Army Corps of Engineers (USACE), 2000. Lake Michigan Potential Damages Study, Progress Report on Activities – 1999. Report Compiled and Edited by Orcatec, p.71.